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16. Abstract

This manual provides guidelines for the design and conduct of soil grouting operations, from the selection of the grout and the design of the injection pattern to construction control methods and evaluation of the completed treatment. This report emphasizes grouting applications associated with excavation and tunneling in an urban environment. It describes the three general grouting techniques - permeation, void filling, and compaction - and covers in detail, six applications: (1) groundwater control, (2) sand stabilization, (3) soil strengthening, (4) backpacking tunnel liners, (5) leak repairs, and (6) tieback anchorages.

A companion report, Volume 1 (FHWA-RD-76-26) is entitled "A State-of-the-Art Report."

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PREFACE

This manual is the second of a two-volume report developed in a study of grouting for the Federal Highway Administration, Department of Transportation. Whereas Volume 1 summarizes the State-of-the-Art in grouting, this volume summarizes current best practices and sets forth guides for grouting design and operational procedures. Volume 2 also discusses: (1) how to select the proper grout material, (2) how to plan for the execution of the job, and (3) how to prepare plans and specifications for a grouting job.

These reports are based on information from four sources: interviews with companies in the grouting or construction business, inspections of grouting jobs, reviews of the literature, and personal experiences of the writers.

The writers appreciate the cooperation, both in the United States and Europe, of those who assisted in the preparation of this report by providing information and input to this study. These companies are listed in the acknowledgements section of Volume 1.

The writers hope that the guidelines presented herein will result in improved grouting practices, particularly in soft-ground tunneling and open-cut construction.

NOTICE

The contents of this report reflect the views of Halliburton Services - Duncan, Oklahoma, which is responsible for the facts and the accuracy of the data presented herein. The contents do not necessarily reflect the official views or policy of the Department of Transportation. This report does not constitute a standard, specification, or regulation.

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Sufficient copies of this report are being distributed by FHWA Bulletin to provide two copies to each regional office, one copy to each division office, and two copies to each State highway department. Direct distribution is being made to the division offices.

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1. INTRODUCTION

A. GENERAL

The art of grouting has been practiced throughout the world over the past 100 years in the construction of foundations and abutments for dams and in the sinking of mine shafts. For many years, grouting was limited to stabilizing rock formations by the injection of cement grout into the joints and fractures. In recent years, less viscous chemical grouts have been developed that can be used to grout the voids in soils too fine for portland cement grout to permeate.

Grouting may be defined as the injection of a fluid material into the voids of the subsoil and formation to stop or reduce water movement, or to consolidate and strengthen the subsoil. The use of grouting has increased over the past two decades and is now applicable to a wide variety of problems in sandy and gravel soils. These are:

a. Water control and sand stabilization in tunneling through cohesionless soil.

b. Water control and underpinning of adjacent buildings when using underground construction.

Several methods can be used in solving problems of flowing sand and water encountered in underground construction. Among these are dewatering, slurry trench and diaphragm wall construction, tieback anchors, freezing, underpinning, grouting, and, in the case of tunneling, compressed air. Only grouting methods, however, are discussed in this manual. A discussion on freezing is included in Volume 1, the State-of-the Art volume. Detailed discussions on freezing, tiebacks and other methods of ground support are given in Volume III, "Lateral Support Systems and Underpinning", FHWA-RD-75-130, April 1976.

The construction and design engineers are faced with a challenge to determine which construction method or combination of methods could be used in any given situation; methods must be used which will meet the safety and environment requirements as well as the final structural requirements. Tunneling and other construction in cohesionless soil below the water table are among the most complex and uncertain civil engineering endeavors, so often the construction involves remedial ground support or water shut-off work when problems are encountered.

B. PURPOSE OF MANUAL

The purpose of this manual is to set forth operational and design guides for using grouting as a construction aid. The primary emphasis is on grouting of soils, particularly as encountered in the underground construction work on tunnels or open trenches. The manual will cover all aspects of grouting from the design of the treatment to the actual operation and the measurement of the results.

2. GROUTING APPLICATIONS IN SOILS

Grouting in soils is applicable primarily to problems with sands and cohesionless soils, particularly below the water table. In past years, grouting was used extensively in the construction of dams; more recently the major emphasis has been in conjunction with open cuts and tunnels in urban areas, usually associated with the construction of rapid transit systems. Whether grouting is a feasible solution to a tunneling or open cut excavation depends on the type and magnitude of the problem, the geology and soil properties, and the geometrical layout and accessibility. The final choice of grouting as a solution will depend on the relative cost and advantages offered in comparison to alternative solutions. This section briefly describes typical situations where grouting is applicable.

A. GENERAL APPLICATIONS AND LIMITATIONS

Grouting in soils can be used to accomplish one or more of the following aims:

a. Waterproof the soil structure.

b. To consolidate the soil.

c. To strengthen the soil.

When used in rock formations, such as in dam construction, grout is placed in cracks or fractures in the rock to stop or control water movement. In soils, the grout is injected into the voids between the particles to block water passages and to provide additional strength in the soil. The proper grout can change loose sand into weak, impermeable sandstone. The grout material can be designed to provide a low viscosity fluid which can permeate the soil voids and solidify to provide a water stop, and thereby prevent ground flow, or to provide solidification for bearing and support of existing structures.

Grouting is normally used in conjunction with excavation in or adjacent to the grouted area. It can be accomplished before excavation, or it can be used as a remedial process after problems have been experienced.

Grouting is not a "cure-all" process, and the designer or contractor should be aware of its limitations. The soil properties must be conducive to the use of grout, i.e., the permeability must be high enough to permit the flow of the grout into the pores without fracturing the soil. The soil or groundwater should not contain chemical constituents which will react negatively with the grout; however, grouts can be modified to overcome this limitation.

A general rule states that the probability of successful groutings is poor if the soil is not essentially sand or cohesionless materials. Generally, clays silts and gumbo soils are not groutable by permeation techniques. There are some techniques, such as compaction grouting or mudjacking, which have been used with reasonable success in non-groutable soils of low permeability. (See the Appendix for a Glossary of Grouting Terms).

B. PERMEATION GROUTING

Permeation grouting consists of filling the voids in a soil deposit with grout fluid, displacing any groundwater present in the soil pores. To prevent fracturing the soil, the grout is injected at a pressure less than the soil overburden pressure.

1. Preventing Loss of Ground

One serious problem faced in excavating cohesionless soil or in tunneling through such soil is loss of ground.

Most bored tunnels are constructed using a shield. The shield is a cylindrical, heavy steel shell which is jacked forward as soil is removed from the tunnel face and as the lining is erected behind the shield. Since the shield provides soil support and protection in the working area, significant soil stability problems occur only at two locations: at the tunnel face being excavated, or behind the shield. Instability or excessive distortion of the finished tunnel lining is rare, but minor ground movements do occur in the region of the shield.

Depending on the soil cohesion and ground water conditions, the soil at the face or behind the shield may be firm, slowly or rapidly ravelling, or running. The severity of ground movements increases with the size of the exposed soil area, time of exposure, and the amount of flowing water. At the face, severe instability may lead to major ground loss or over-dig, causing excessive settlement at the ground surface. This problem is shown in Figure 1. In dry sand, the ground loss may be as high as two percent of the excavated soil volume. Flowing sand caused by groundwater does not stop at the angle or repose, but may fill the greater part of the tunnel before it stops flowing or depletion of water source.

This same situation can develop in lenses of cohesionless soil encountered in cohesive soil. If uncorrected, running sand in lenses may cause some settlement, but not to the magnitude of that mentioned above. If running sand is anticipated, grouting can be used in advance of excavation to supply the necessary soil strength to stabilize the soil and allow tunneling with minimal ground loss. The grouting can be done from the face, or it can be performed from the surface if site conditions permit. Figure 2 shows both methods.

In order to consolidate the soil for tunnel excavation, the following procedure is practical:

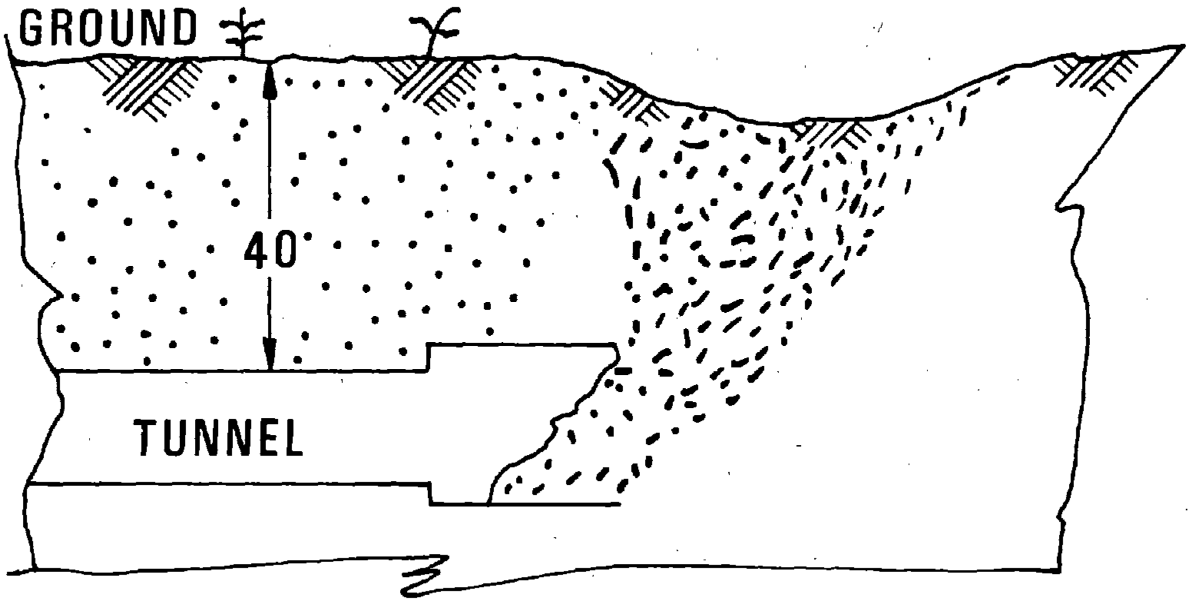
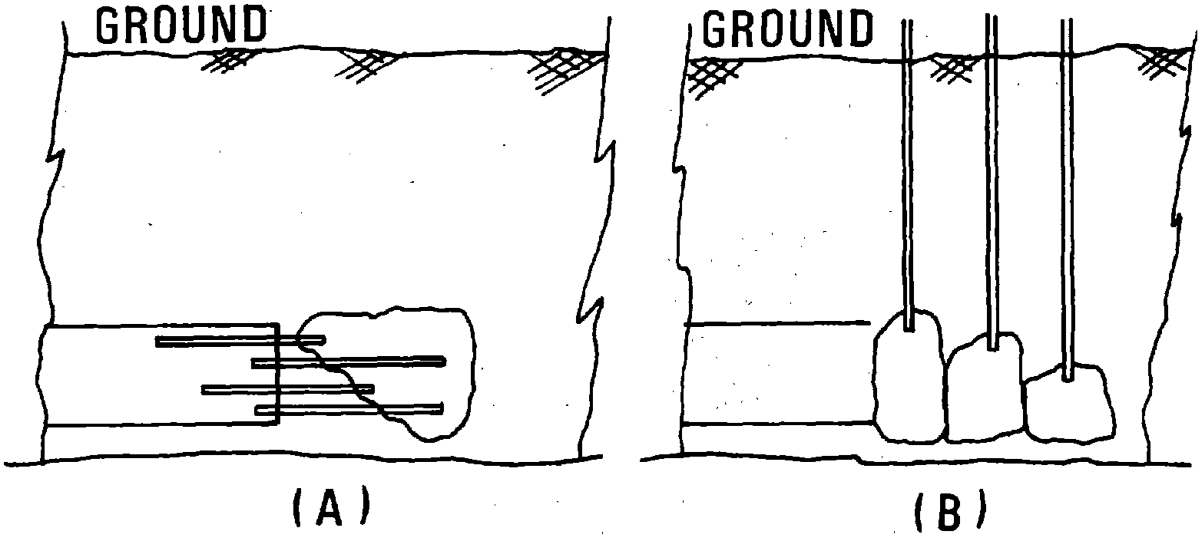


Figure 1. Ground surface settlement caused by running ground.



(A)

(B)

Figure 2. Consolidation of tunnel material to prevent running ground.

(1) Use a low-strength grout with quick-setting ability.

(2) Inject grout into the soil for 20 to 30 feet ahead of the tunnel excavation.

(3) Repeat step 2 when excavation is within 5 feet of ungrouted soil.

When an excavation is supported by a system that is not watertight, such as soldier beams and lagging, significant ground losses can be experienced in excavating and placing lagging boards. Remedial grouting can be done through pipes placed into the soil behind the lagging. A fast-setting chemical grout of medium strength should be used. Details on grout selection will be found in Chapter 4.

2. Water Shutoff

(a) Grouting Under Dams

The foundation material under dams has been grouted as standard procedure for many years to prevent groundwater flow under the dam. The technique is well documented in technical manuals by government agencies(1)*. Until recently, most dams have been built over rock foundation support. Grouting was done by injecting portland cement grout into drilled holes which intersected cavities, fractures and permeable zones in the rock.

For dams built over gravel and sand foundations, grouting is done in two stages. First, a portland cement grout is used where possible to fill the larger voids; then, a chemical grout is used to penetrate into the void spaces of the finer sands. The grout is normally used to develop an impervious curtain under the dam on or near the axis of the dam. For dams less than 200 feet in height, a single row of injection holes is used; for taller dams, multiple rows are used.

(b) Grout Curtains

Grout curtains are also used in other applications where a water barrier is required. For example, it can be used in cut-and-cover construction behind a previous ground-support wall, to prevent groundwater flow into the excavation and lowering of the water table under near-by structures.

The grout curtain is normally placed with 2 or 3 rows of injection pipes as shown in Figure 3.

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* Underlined numbers in parentheses identify references in Appendix, page 92.

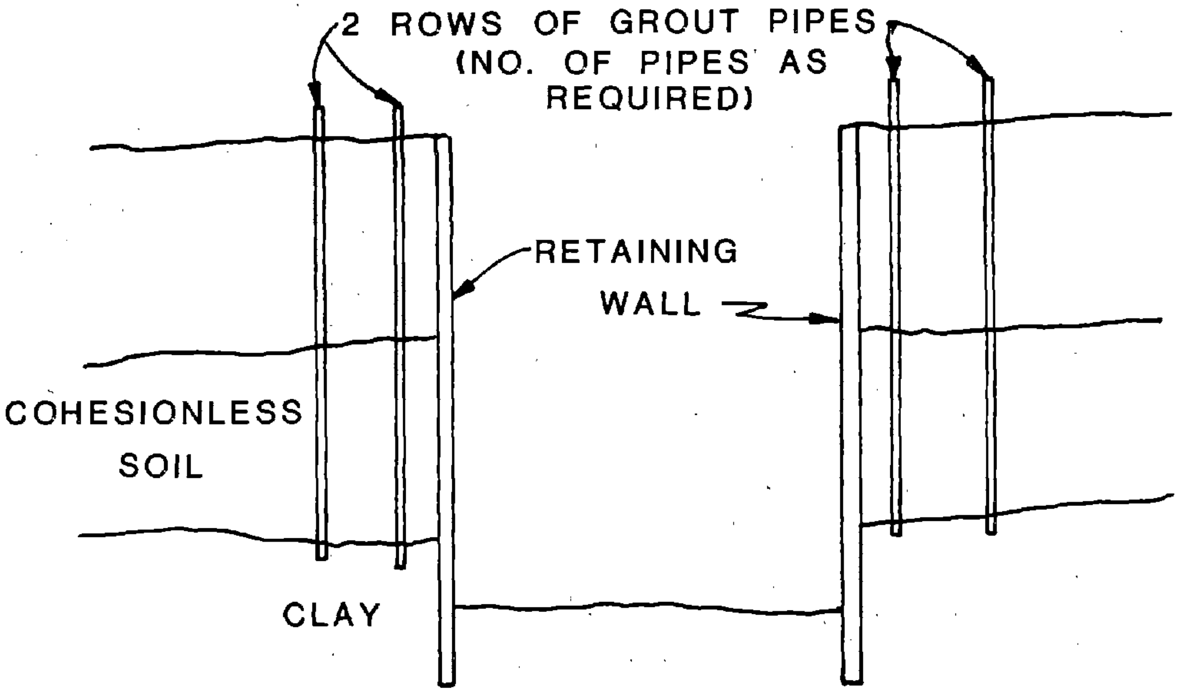


Figure 3. Grout curtain layout

When the grid layout contains three or more injection pipes, the odd or middle row of pipes is spaced alternately with the pipes in the outer rows. The curtain should be deep enough to reach into the impervious layer below to prevent movement of water under the curtain. The spacing of the holes depends upon the type of grout used, soil permeability, grout viscosity, maximum pressure and permissible flow rate. (See Chapter 5 for planning details).

3. Stabilization of Soil

One of the major applications for grouting is the stabilizing of cohesionless soil to permit excavation without running ground or water problems. This application is encountered frequently in tunneling through cohesionless soils.

Grouting can be applied around the periphery of a planned tunnel in order to lower costs of grouting, or it can be applied to the entire area to be excavated. Figure 4 shows a grouting job to stabilize the soil prior to excavating two tunnels under twenty-six railroad tracks that remained operational during the probject. A four-foot tunnel was bored through soil completely grouted with chemical grout. The fourteen-foot tunnel was bored through a zone grouted peripherally. It was necessary to grout ahead of the shield occasionally during excavation of the larger tunnel, but considerable grout was saved by grouting peripherally.

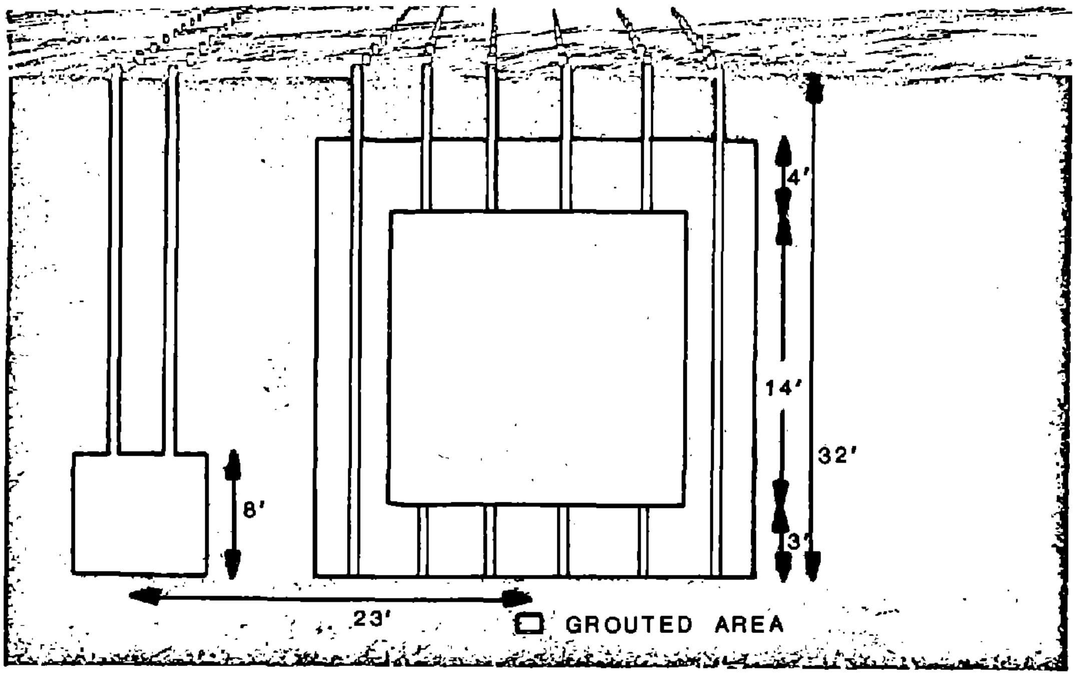


Figure 4. Grouting for tunnel stability

4. Strengthening of Soil

An underground project in an urban area is typically surrounded by buildings, other structures, and a variety of utilities. These must be protected against damage during the construction. It is nearly impossible to fully prevent ground movements and settlements due to tunneling and deep excavations. Moderate settlements, however, are acceptable, provided they cause no cracking or other damages to the structure.

Planning for major excavation projects should always include an evaluation of the effects of the excavation on the existing structures. These structures may need to be underpinned or otherwise protected, purchased and resold later, or purchased and demolished.

Grouting can be used in strengthening the foundation soil beneath structures above or adjacent to the proposed excavation. Figure 5 shows how the grout treatment stiffens and strengthens the foundation soil and effectively causes the foundation load to be transferred downward to a lower bearing strata.

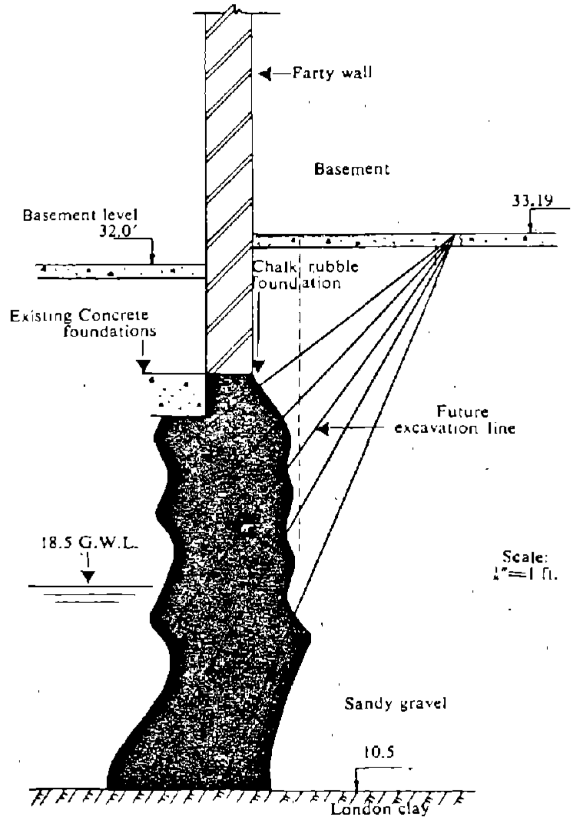


Figure 5. Use of grouting to strengthen soil under buildings

In grouting as shown in Figure 5, injection pipes are placed from the surface and inclined to provide coverage of grout over entire area below exisitng foundations. A grout of sufficient strength to provide load bearing capacity is selected for this application.

In cut-and-cover, or deep excavations, bottom instability is encountered when upward water flow creates gradients large enough for piping or quicksand conditions to occur. A permeable stratum below the bottom which is covered by a less pervious soil layer may cause the stratum to "blow up" if the hydrostatic uplift pressure is too great. This problem is shown in Figure 6 (a).

Grouting can be used effectively to alleviate this problem. A layer of soil can be consolidated with grout prior to excavation to provide a water barrier of sufficient strength between the sidewalls to resist the thrust of the groundwater head, as shown in Figure 6 (b). Another approach would be to place a shallow layer of grout across the bottom to prevent water movement, and then leave enough weight of soil on the grouted bottom to hold the hydrostatic head.

This approach would entail deeper side walls and may be more expensive than grouting the greater area. Details on equipment selection and planning are given in Chapter 5.

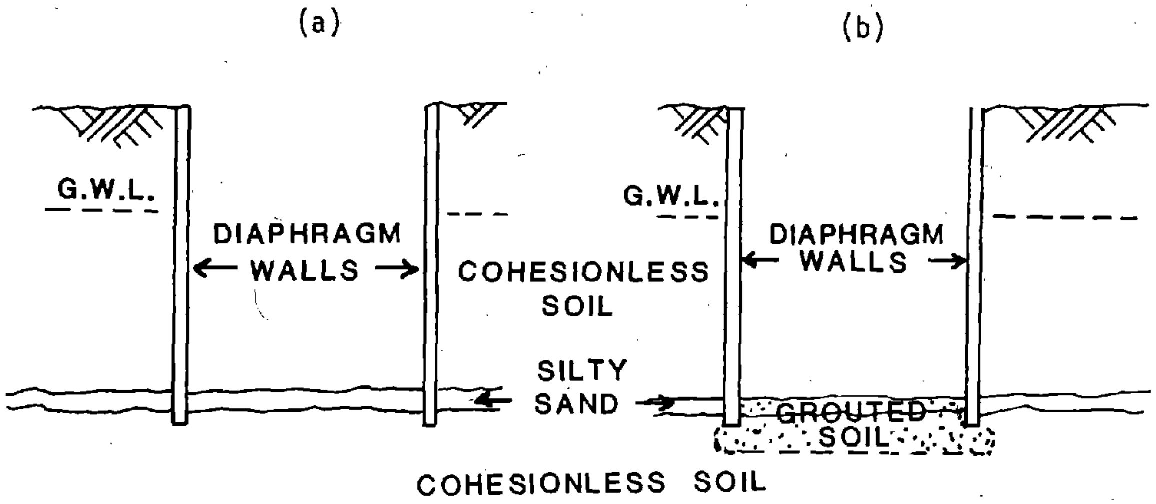


Figure 6. Hydrostatic water problem and solution by grouting

5. Leak Control

Leakage into concrete structures below the water table is common. Leaks occur through cracks, joints, porous spots, etc. They can be corrected by drilling into the faulty spot with a small concrete drill and injecting the grout into the structure to provide the desired sealing effect. Detailed application information is given in Chapter 9.

C. VOID FILLING

1. Mudjacking (Slab Leveling)

Mudjacking, or slab leveling, consists of injecting a heavy grout (usually cement or clay type) beneath a floor slab, tank floor or similar structure to fill any voids and to raise the structure. With appropriate techniques and controlled pressure, such slabs or tanks can often be leveled. This method is not applicable for raising settled or cracked buildings. Detailed procedures for this type of grouting will be found in Chapter 9.

2. Compaction Grouting

A variation of mudjacking called compaction grouting is used to consolidate cohesive soil which is too impermeable to be grouted by permeation. Compaction grouting consists of injecting a stiff, viscous grout into the soil, actually displacing and densifying the soil around the grout hole. This technique can be used to strengthen soil under a structure, as shown in Figure 7, provided the structure is deep enough to permit the higher pressures required. Details are given in Chapter 9.

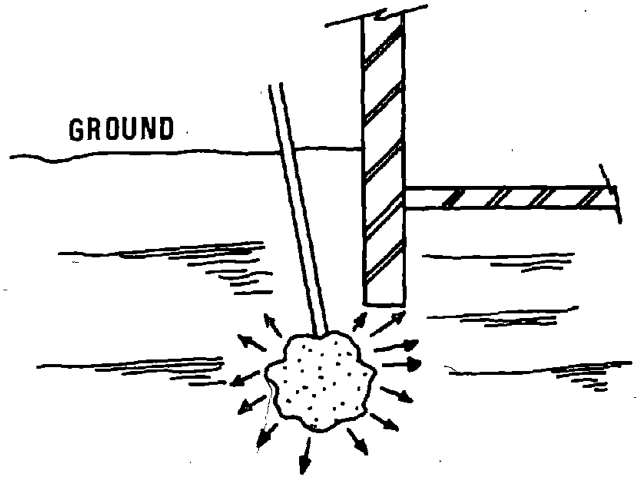


Figure 7. Compaction grouting to density soil for strength

3. Backpacking of Tunnels

When tunnels are bored and the tunnel lining set in place, it is essential to backfill the tail void space before significant quantities of soil enter that space. Loss of ground around the tunnel can cause settlement of the ground surface. This void filling, called backpacking, is usually done partly or fully by cement grouting; the grout fill should be placed as quickly as possible after the lining is installed to prevent settlement in the void area around the lining. See Chapter 9 for further information.

D. SUMMARY

Grouting is an acceptable method for solving problems dealing with running ground, groundwater movement and ground support under structures. Grouting can be considered for the above problems if the soil is permeable enough to accept the grout. Successful applications in each of the above areas have shown the feasibility of the use of grouting.

Chapters 4, 5 and 6 will give details on procedures, equipment and grout materials used to perform the actual operations.

Mudjacking and compaction are special applications of grouting which are detailed in Chapter 9.

3. SITE INVESTIGATION PROCEDURES

A. PARAMETERS TO CONSIDER

A thorough site investigation should have top priority for any grouting operation since the applicability depends so heavily upon soil conditions. The site conditions must be known to intelligently design and perform grouting operations. Information desired from a study of the site should include as a minimum:

(1) Surface site conditions.

(2) Ground and hydrological conditions.

(3) Soil profile.

(4) Engineering soil properties.

It is possible that a site investigation has already been made by a qualified soils engineering firm, especially if the site is in a well-developed urban area. A previous investigation might have been made without consideration of grouting; however, it should provide sufficient background information so that a minimum of additional investigation is necessary for planning a grouting operation. As a basis for proper planning, this chapter will set forth the information needed from a site investigation.

B. SURFACE SITE CONDITIONS

The site survey should determine physical data to provide answers to these questions:

(1) Can the grouting be done from the surface?

(2) What would be the best location for the pumping and mixing equipment and the storage tanks for the chemical components? What space is available for storage of other materials, such as pipe?

(3) Are there buried utilities on the site which should be protected?

C. GROUND AND HYDROLOGICAL CONDITIONS

The ground and hydrological conditions should be investigated by boring test holes or by other means so that the following information can be determined:

a. Ground type - soil, rock or mixed.

b. Soil grading.

c. Permeability and porosity of the soil.

d. Water table depth.

e. Groundwater flow rate.

f. Groundwater chemical properties.

g. Moisture content of soil (dry, wet or saturated).

A soil profile should be made for the site at several locations. The profile of the soil subsurface is very important, especially if tunnels are to be excavated in soft ground (or cohesionless soil).

Data on groundwater flow should be obtained by in situ tests. A fluorescein type dye could be injected into one borehole, and the time measured for the dye to travel to another borehole. This information would be helpful in establishing the set time needed for the grout.

The groundwater on the site may contain dissolved materials that will materially affect the pump time and/or the final quality of the grouting material. These materials may be dissolved from the soil or may have leaked from pipelines carrying sewerage, industrial wastes, or chemicals. A laboratory analysis of the groundwater should include pH, sulfides and calcium. A low pH affects silicate or urea-formaldehyde grouts and the presence of calcium has a detrimental effect on urea-formaldehyde grout.

The moisture content of the soil can be determined in the laboratory. The standard method of Laboratory Determination of Moisture Content of Soil, ASTM D 2216-71, can be used for this test.

The soil grading, or particle size analysis, and the permeability and porosity are normally determined by laboratory tests of samples obtained from the test boreholes.

D. DETERMINATION OF SOIL PROPERTIES

When grouting is being considered as a part of a project involving soil excavation, it is necessary to know soil properties in order to answer the following questions:

(1) What value can the grouting have for the construction being considered?

(2) Is grouting feasible for the site being considered?

(3) If grouting is possible, what would be the best grout to use?

(4) What would the grouting cost?

The determination of permeability and porosity will aid in answering the questions above, since the permeability controls the groutability and the type of grout used, and the porosity determines the amount of grout needed, which affects the cost for the job.

A particle size analysis can be used initially in determining groutability. This analysis is made on a sample prepared according to ASTM Standard Method D 421-58 and analyzed in accordance with ASTM Standard Method D 422-63.

A "rule of thumb" for determining groutability is that the soil is not groutable if over 10% of the sample will pass the #200 sieve. Grouting may be somewhat successful when soil is in the range of 10%-20% passing if a very low viscosity grout is used; however, it would probably be either by compaction or by fracturing rather than by permeation.

If the particle-size analysis test indicates that the soil is groutable, further laboratory tests should be made to find the permeability of the soil.

1. Permeability Determination

The coefficient of permeability can be determined by a constant head permeability test, performed in accordance with ASTM Standard Test Method D 2434-68.

The coefficient of permeability, k, has the dimension of a velocity, i.e., distance divided by time. Normally, this is expressed in cm/sec. Figure 8 shows a guide (2) for correlation between the effective size, D_{10}, (determined from the particle size curve) and the permeability coefficient k. It also shows the soil character, possible dewatering methods and types of grout which are applicable for various permeability coefficients.

The weak point in laboratory determination of permeability is the difficulty of ensuring that the amount of compaction and the structure of the soil sample in the permeameter is representative of that in the ground. The recompacted samples will only be approximations of the soil structure in place.

Therefore, when checked for flow rates and permeabilities, the samples will usually produce different flow rates than the same soil tested in situ. It is good practice, however, to collect these

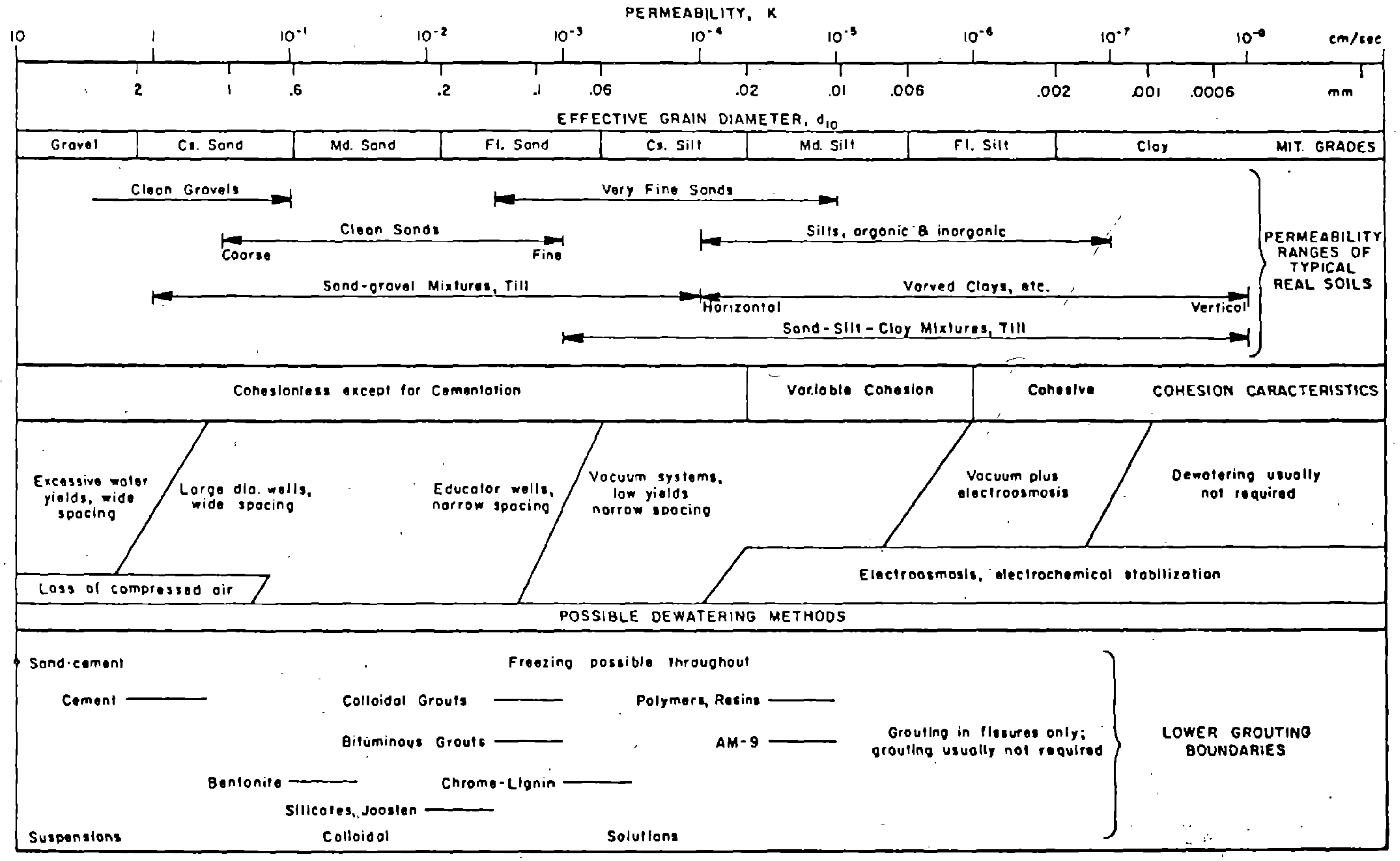


Figure 8. Correlations of permeability and grain size (2).

samples and perform laboratory tests to obtain an indication of the permeability before going to the additional expense of in situ testing. If the laboratory tests give a permeability coefficient of 10^{-5} cm/sec or less, the groutability of the soil is doubtful.

2. Porosity Determination

Porosity of the formation sample can be estimated in the following manner (3). Using the grain-size distribution curve, determine the median grain diameter (in millimeters) at the 50% point of the curve. Then find the sorting ratio, So, by dividing the diameter at the 25% point by the diameter at the 75% point of the curve and taking the square root of the quotient ($So = \sqrt{D25/D75}$). The approximate porosity can then be found in Table 1 at the intersection of the Sorting Coefficient and Median Diameter. The porosity value at L would be used for strata above the water table and the value at P for strata below the water table.

Table 1. Porosities of dry-loose (L) and wet-packed (P) sand (3).

So	Size →	Coarse		Medium		Fine		Very Fine	
	Sorting ↓	Upper	Lower	Upper	Lower	Upper	Lower	Upper	Lower
1.0 1.1	Extremely well sorted	L 44.7 P 43.1	L 44.7 P 42.8	L 46.6 P 41.7	L 45.6 P 41.3	L 45.7 P 41.3	L 48.7 P 43.5	L 49.8 P 42.3	L 51.4 P 43.0
1.1 1.2	Very well sorted	L 42.7 P 40.8	L 44.1 P 41.5	L 44.3 P 40.2	L 43.9 P 40.2	L 44.8 P 39.8	L 47.5 P 40.8	L 49.6 P 41.2	L 51.8 P 41.8
1.2 1.4	Well sorted	L 41.2 P 38.0	L 43.7 P 38.4	L 42.5 P 38.1	L 43.9 P 38.8	L 44.7 P 39.1	L 46.0 P 39.7	L 49.5 P 40.2	L 51.9 P 39.8
1.4 2.0	Moderately sorted	L 37.4 P 32.4	L 37.6 P 33.3	L 39.4 P 34.2	L 41.0 P 34.9	L 41.9 P 33.9	L 44.1 P 34.3	L 48.1 P 35.6	L 52.6 P 33.1
2.0 2.7	Poorly sorted	L 33.5 P 27.1	L 34.9 P 29.8	L 36.4 P 31.5	L 38.0 P 31.3	L 41.8 P 30.4	L 47.3 P 31.0	L 52.7 P 30.5	L 57.0 P 34.2
2.7 5.7	Very poorly sorted	L 33.3 P 28.6	L 30.2 P 25.2	L 37.2 P 25.8	L 38.8 P 23.4	L 48.3 P 23.5	L 55.0 P 29.0	L 57.8 P 30.1	L 63.2 P 32.6
	Median Diameter, mm	1.000 0.710	0.710 0.500	0.500 0.350	0.350 0.250	0.250 0.177	0.177 0.125	0.125 0.088	0.088 0.044

E. IN SITU TESTING

1. Permeability Tests

Permeability obtained by in situ testing provides a value which is based on an unaltered soil structure. This determination helps establish the type of grouting material that can be used effectively; the test also provides the injection rates and the pump pressures for water.

Tests can be made in the boreholes where samples were obtained, or tests can be conducted at other spots using drive rods or bored holes. A source of water and the necessary pumping equipment must be available at the site. Driving or drilling equipment must also be available if new holes or drive rods are to be used.

The type of test holes used is determined by the nature of the soil and the depth at which tests are to be made. Driven grout pipe may be preferred for depths down to about 50 feet and where the soil is relatively soft or cohesionless; for greater depths or for harder soil it will be necessary to use boreholes and set casing in the hole.

Either constant-head or falling-head field permeability tests can be performed in boreholes. The constant head tests may be conducted either with drive rods or with open end casing and a packer. In the constant head tests using drive rods, water is pumped at a constant pressure into the test hole with the rod driven into the stratum to be investigated. Pump rates and fluid volume are measured for a given time and the permeability calculated from the data obtained. This procedure is included in the Appendix as Exhibit 1-B. In the constant head packer test, data can be obtained in a similar manner on each stratum as the hole is drilled. In this instance, the tests can be made using perforated pipe below a packer set in the lower part of the casing. This procedure is Exhibit 2-B in the Appendix.

The falling head test employs a piezometer installed in a borehole for the purpose of measuring the rate of the falling water level against time. This method is an economical one which can be used in a wide range of soil types. A piezometer also serves the additional function of measuring the excess hydrostatic pressures during the field operations. The procedure for this type of test is Exhibit 3-B in the Appendix.

The Standard Penetration Test (ASTM D 1586-67) may be applicable to indicate relative density of the cohesionless soil. Tests should be performed and data recorded so subsequent tests after grouting can be compared.

4. GROUT PROPERTIES AND SELECTION

A. GENERAL

The choice of the correct grout materials is essential to successful grouting operations. Frequently, several grouts might be appropriate.

Several factors should be considered during the initial selection of a grout material:

(1) Soil permeability, or effective particle size.

(2) The purpose for grouting.

(3) Chemical constituents of soil and groundwater.

(4) Cost of the grout.

When several grouts are suitable, the cost of the grout determines the order of preference. The choice can then be narrowed to a specific grout (or grouts) by an evaluation of grout material properties.

B. INITIAL GROUT SELECTION

The grout required depends upon whether it will be used for waterstop or strengthening purposes. For waterstop purposes, the grout need not develop a tremendous strength; it only needs to be strong enough to hold the expected hydrostatic water head. The grout used for strength purposes must solidify or consolidate a soil to impart additional load-bearing characteristics.

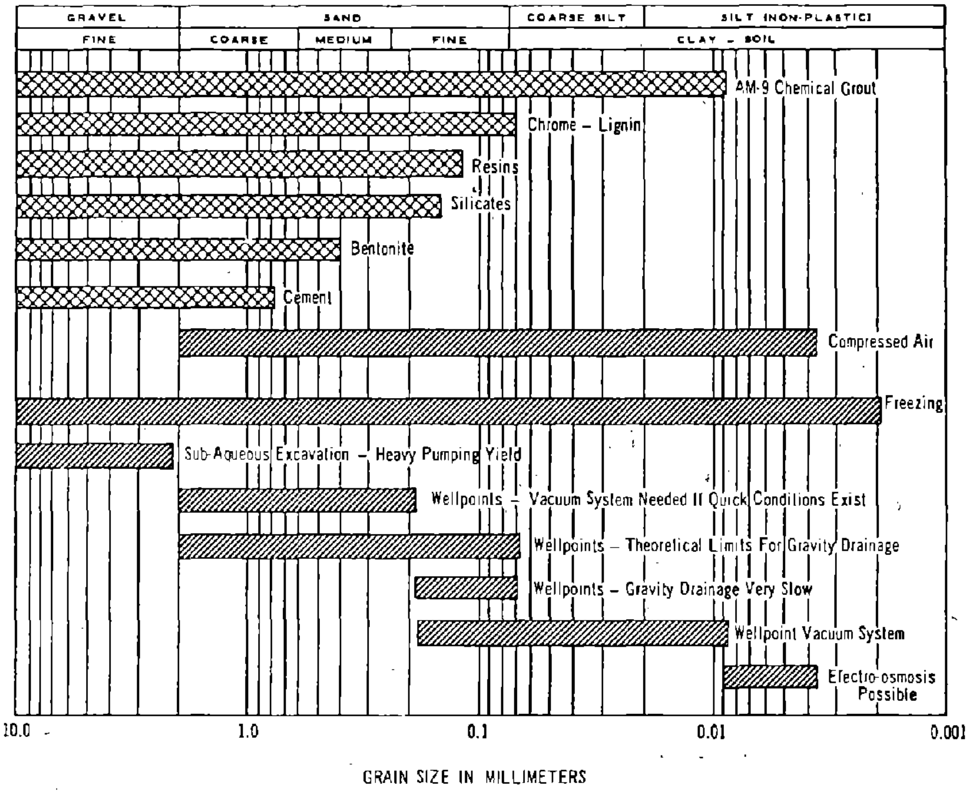
Table 2 shows a variety of grouts and lists their applicability for waterstop or consolidation purposes (4). This is a guide which can help in tentatively selecting a general group of applicable grouts for a proposed job.

The grouts can be classed into two general groups - particulate grouts and solution grouts. Most chemical grouts are considered solution grouts; but actually some of them have very fine chemical particles in suspension, and these are actually collodial solution grouts.

The permeability of the soil, or the effective grain size (D_{10}), controls the grout that can be injected into the soil pores. Figure 9 relates grout type to the grain size of the soil. Based on the effective grain size, this graph indicates the types of grouts that could be given further consideration. If one knows only the permeability, k, he can determine the corresponding effective grain size from Figure 8 and use it in Figure 9 to determine applicable grouts.

Table 2. General grout uses (4).

Class	*Example*	*Viscosity* cP	*Gel time range* min	*Specific gravity*	*Approximate hydraulic gradient at failure in* 1 cm/sec *sand*	*Sinking speed in water-laden soil* (k = 1 cm/sec) cm/sec	*Special fields*		
							Water-stopping	*Consolidation*	
							Fine soil	*Medium strength**	*High strength*
Silica gel low concentration	Silicate-bicarbonate	1·5	0·1–300	1·02	200	0·04	✓	✓	
Silica gel high concentration	Silicate-formamide	4–40	5–300	1·10	500+	0·08 and less			✓
Chrome lignin	TDM	2·5–4	5–120	1·10	500+	0·12	✓	✓	
Vinyl polymer	AM-9	1·3	0·1–300	1·02	500+	0·05	✓	✓	
Methylol bridge polymer	UF	6	5–300	1·08	500+	0·04			✓
Oil-based unsaturated fatty acid polymers	Polythixon FRD	10–80	25–360	0·99–1·05	—	0·02 and less			✓



From: Am. Cyanamid

Figure 9. Soil limits for grout injectability.

Figure 9 shows the chemical grouts at low concentrations normally used in field operations. When concentrations are increased to obtain greater strengths, viscosities also increase and limit the grout to more permeable soils. This will be discussed more completely later in the chapter. In general, cement grout should not be used in soils with coefficient of permeability, k, smaller than 10^{-1} cm/sec, and clay grouts when $k < 10^{-2}$ cm/sec. In soil with $k > 10^{-2}$ cm/sec, grouts may have a viscosity of 10 cp (centipoise) or more without disadvantage, except when used close to the surface, where injection pressures must be kept low. Chemical grouts can generally be used in soils with k up to 10^{-5} cm/sec with good results.

The information about chemical constituents of the groundwater and soil should be checked to see if it eliminates any grouts. A low pH affects silicate or urea-formaldehyde grouts, sulfides affects AM-9, and calcium affects urea-formaldehyde grouts. This would not eliminate these grouts, but they would be more expensive to use. At this point, one should be able to determine which grouts can be used. For example, if the soil has an effective grain size of 0.2 mm ($k \simeq 10^{-2}$ cm/sec), cement or bentonite grouts could not be used, but any chemical grout might be acceptable. Establishing a preference from this group might be done on the basis of cost. Table 3 gives a relative cost basis of various chemical grouts compared to cement. This shows that the 15% silicate grout would be the least expensive for the stated example. Since these are approximations and may change from time to time, actual costs should be determined in each specific application.

Table 3

Cost Comparisons of Grout

Type of Grout	Basic Cost Figure
Portland Cement	1.0
Silicate Base - 15%	1.3
Lignin Base	1.65
Silicate Base - 30%	2.2
Silicate Base - 40%	2.9
Urea-formaldehyde Resin	6.0
Acrylamide (AM-9)	7.0

(Courtesy of American Society of Civil Engineers)

C. CONSIDERATION OF GROUT PROPERTIES

After a group of grouts has been selected, the specific grout selection can be made by examining the grout properties and the properties of the soil samples grouted with the proposed grouts. The grout properties will help in determining the grout to be tested in the soil samples.

Since both particulate and solution grouts are used in grouting of cohesionless soils, properties of both types will be considered. Important properties are viscosity, setting time, stability, water tightness, toxicity and strength.

1. Viscosity

The permeation of a solution grout into a soil of a given permeability is governed by the grout viscosity. The permeation of a particulate grout is controlled in the early stages by viscosity, but in the later stages by grout shear strength. In order to penetrate a formation at a reasonable pressure and flow rate, the size of the largest suspended particles cannot be greater than about one-third the size of the voids. For soil consisting predominately of one grain size, grout particles should be less than one-tenth of the mean particle size of the soil. Figure 10 shows the limiting grain size of soils which can be successfully grouted by clay or cement grouts; however, this should be used only as a general guide (1d).

Another way of expressing the relationship between the particle size of the grout and the grain size of the soil to be grouted is by the groutability ratio, GR:

$$GR = \frac{D_{15}}{D_{85}}$$

where D_{15} = the 15% size of the soil to be grouted (Fifteen percent of the soil has finer grain sizes)

and D_{85} = the 85% finer grain size of the grout.

Based on tests by the Corps of Engineers (5), the limits of groutability based on the GR value are shown in Figure 11. The tests were limited to two cement grouts, but they do give a minimum ratio of 11 for determining groutability with cement grouts.

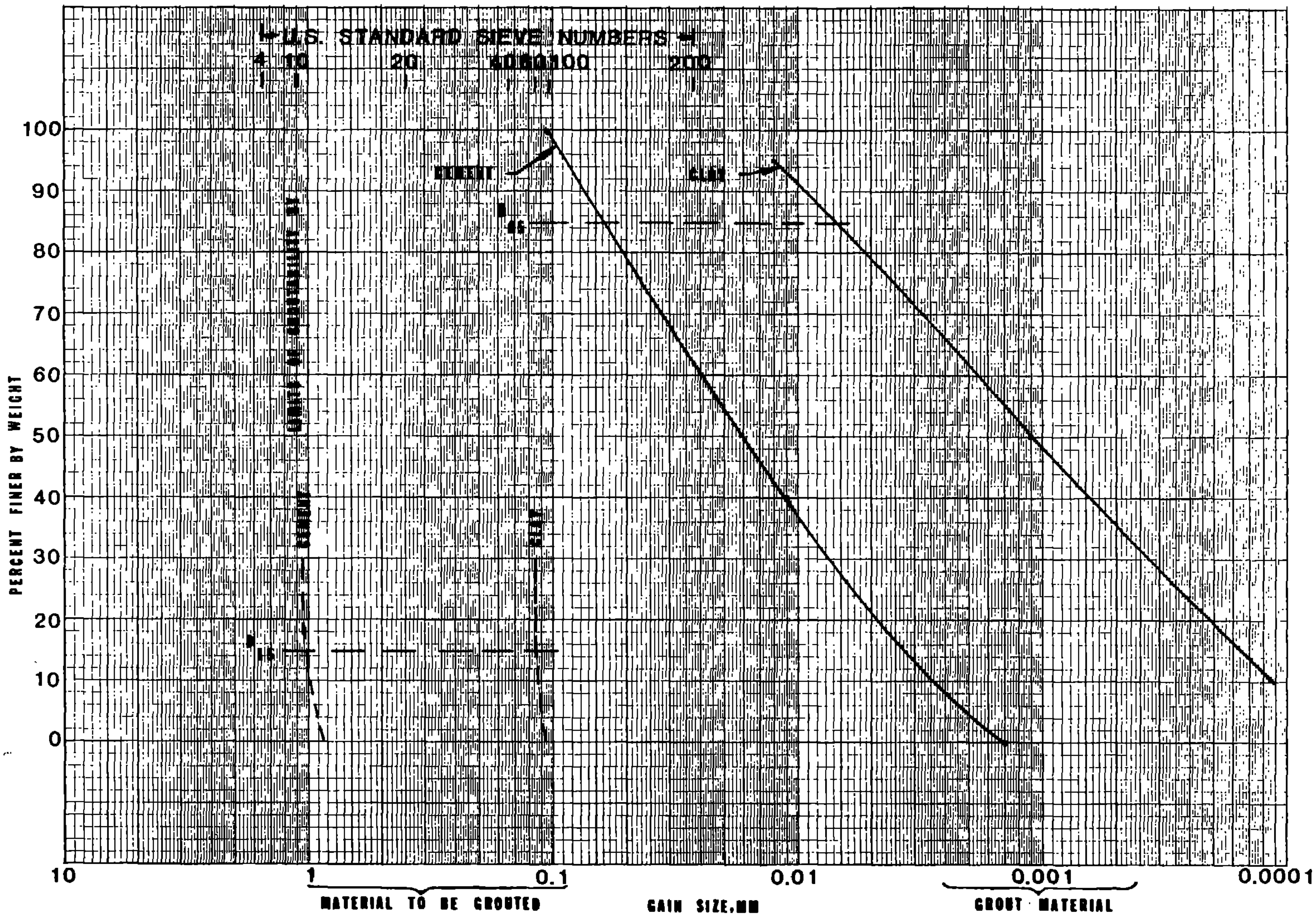


Figure 10. Soil and grout materials grain size curves (1d).

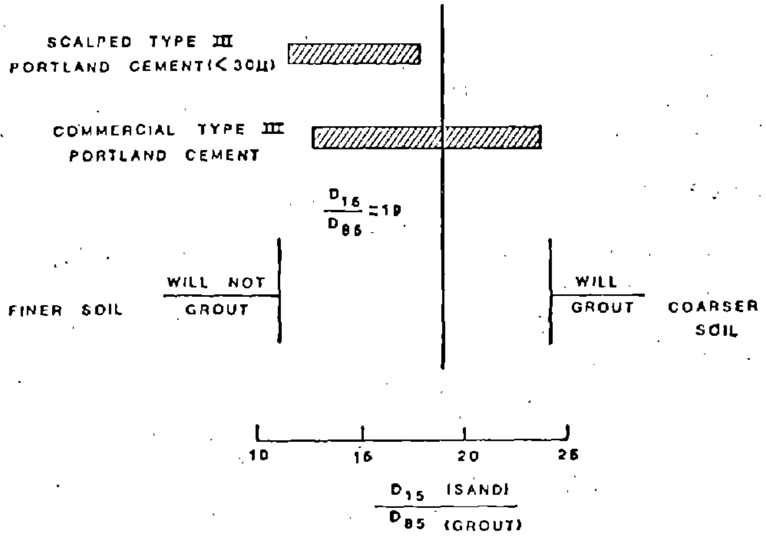
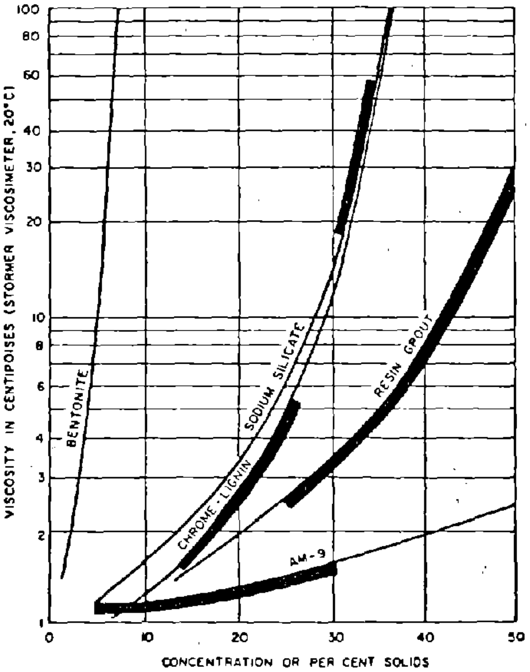


Figure 11. Limits of groutability of sands by particulate grouts (5).

The viscosity of the chemical grouts varies with the percentage of solids in solution. This is shown in Figure 12 for several chemical grouts and a bentonite grout (6). The AM-9 grout is a true solution, the bentonite is a particulate grout, and the balance are chemical grouts of a colloidal nature. This graph shows how the increased concentration of chemicals in each grout increases the viscosity.



Courtesy: Am. Cyanamid

Figure 12. Viscosities of various grouts.

Table 4 gives the properties of currently used grouts. Although the approximate viscosity or range in viscosity is given, the actual viscosity of the grouts being considered should be determined on prepared samples in a laboratory with a rotation viscosimeter. The result will be an apparent viscosity, but it will give comparable values from one grout to another. Tests should be made at approximately 68°F. If the temperature at the job site will vary greatly from the temperature of lab tests, the lab tests should be made at expected temperatures. An increase in temperature will reduce the viscosity, but the change will be minimal; therefore, comparative tests between grouts could be made at room temperatures.

Viscosity also increases with time as the grout is being injected. Most grouts begin to increase immediately after mixing as shown on the upper curve in Figure 13. This makes the grout progressively harder to inject, thereby increasing the injection pressure. The AM-9 (PWG) grout shown in the lower curve remains at its original viscosity until set occurs.

The grout with the lower viscosity will enter the pores of the soil at a lower pressure than grouts having higher viscosity. The grouts should be considered in order from the lowest viscosity grout.

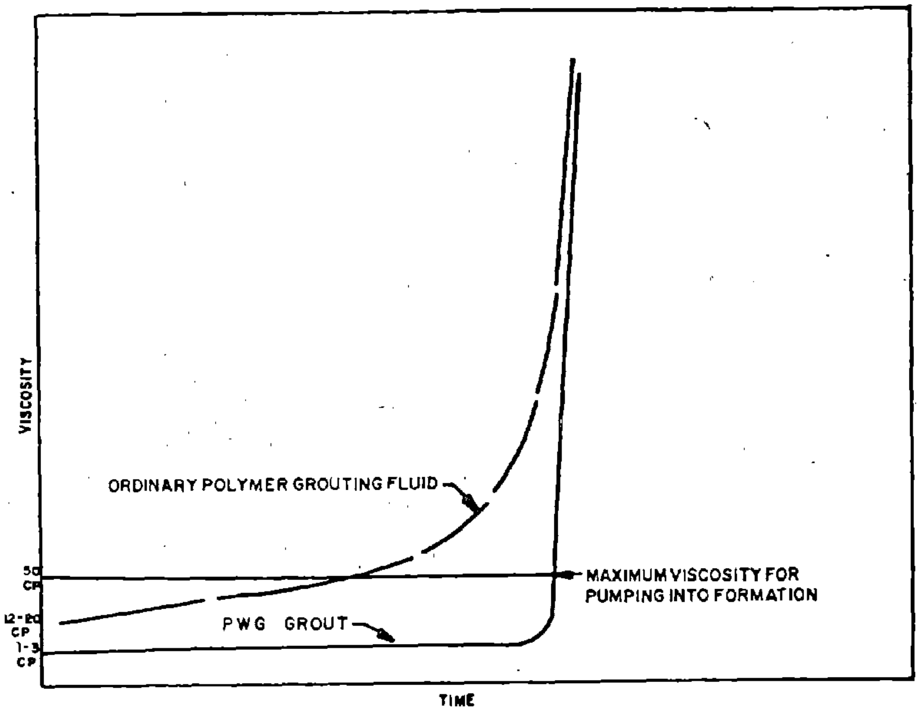


Figure 13. Grout viscosity increase with time.

2. Setting Time of Grouts

The setting time for chemical grouts, sometimes called gel time or induction period, is that time between the addition of the catalyst to the gel forming solution and the formation of a gel. With cement grouts, it is the time required to harden or thicken to a point of immobility or nonpumpability.

Setting time for cement grout is a matter of hours. The time for a portland cement grout with a 0.5:1 water-cement ratio is about 4 hours at an ambient temperature of 80°F. The pumping time of this grout would be about 70% of the set time, or approximately 3 hours. Increasing the water-cement ratio would increase the set time and pumping time proportionally.

The setting time of most chemical grouts can be varied from a few minutes to an hour or longer; some can be compounded to set in a few seconds after mixing components together. Variations are obtained by the amount of catalyst added, an increase in temperature, or the addition of accelerators. Tables 2 and 4 give the range in gel time for a number of chemical grouts.

Setting time also varies according to the process used. In the Joosten (two-shot) process, setting time is instantaneous when the two fluids meet. The setting time for a one-solution batch of a chemical grout must be sufficiently long to insure placing the grout before it sets. The very short setting times are best obtained using a two-stream method.

The setting time affects the grout choice primarily when a short time will be required, viz, when injecting the grout into an area with flowing groundwater. Flowing groundwater tends to move the grout as a mass in the direction of flow, possibly taking the grout completely out of the desired area. A shorter gel time will be necessary in maintaining control of the job.

The setting time for the tentative grout should be checked in laboratory tests. Small samples, mixed in proper proportions, should have the set time measured at the same temperatures used in the viscosity tests. These tests could be combined with the viscosity tests. The design of the grout mixture should be adjusted to give the setting time needed for the job.

3. Stability, Water Tightness and Toxicity

Stability, or permanence of the grout in the soil, may be important in the particular grouting application being considered. If water shutoff is desired for a limited time only, stability is relatively unimportant. Silicate grout may be a nonpermanent gel when used in the two-shot injection system, depending on the reactant used, but most other grouts are considered permanent.

Table 4. Properties of currently used grouts.

GROUT MATERIAL	CATALYST MATERIAL	UNCONFINED COMPRESSIVE STRENGTH (PSI) OF GROUTED SOIL	VISCOSITY (CENTIPOISE)	SETTING TIME MINUTES	TOXICANT*	POLLUTANT**
SILICATE BASE						
LOW CONCENTRATION	BICARBONATE	10-50	1.5	0.1 - 300	NO	NO
LOW CONCENTRATION	HALLIBURTON CO. MATERIAL	10-50	1.5	5 - 300	NO	NO
LOW TO HIGH CONCENTRATION	SIROC - DIAMOND SHAMROCK CHEMICAL CO.	10-500	4-40	5 - 300	NO	NO
LOW TO HIGH CONCENTRATION	CHLORIDE - JOOSTEN PROCESS	10-1000	30-50	0	NO	NO
LOW TO HIGH CONCENTRATION	ETHYL ACETATE SOLETANCHE & HALLIBURTON	10-500	4-40	5 - 300	NO	NO
LOW TO HIGH CONCENTRATION	RHONE-PROGIL 600	-	-	-	-	-
LOW TO HIGH CONCENTRATION	GELOC-3 H. BAKER CO.	10-500	4-25	2 - 200	NO	NO
LOW TO HIGH CONCENTRATION	GELOC - 3X	10-250	4-25	0.5 - 120	NO	NO
LIGNIN BASE						
BLOX-ALL	HALLIBURTON CO. MATERIAL	5-90	8-15	3 - 90	YES	YES
TDM	CEMENTATION CO. MATERIAL	50-500	2-4	5 - 120	YES	YES
TERRA-FIRMA	INTRUSION CO. MATERIAL	10-50	2-5	10 - 300	YES	YES
LIGNOSOL	LIGNOSOL CO. MATERIAL	10-50	50	10 - 1000	YES	YES
ACRYLAMIDE BASE						
AM-9 ***	DMAPN and AMMONIUM or SODIUM PERSULFATE	50-500	1.2 - 1.6	0.1 - 1000	YES	YES
FORMALDEHYDE BASE						
UREA-FORMALDEHYDE	HALLIBURTON CO. MATERIAL	OVER 1000	10	4 - 60	YES	YES
UREA-FORMALDEHYDE	AMERICAN CYANAMID CO. MATERIAL	OVER 500	13	1 - 60	YES	YES
RESORCINOL FORMALDEHYDE	CEMENTATION CO. MATERIAL	OVER 500	3.5	—	YES	YES
TANNIN - PARAFORMALDEHYDE	BORDEN COMPANY MQ-8					
GEOSEAL MQ-4 & MQ-5	BORDEN COMPANY MATERIAL					
UNSATURATED FATTY ACID BASE						
POLYTHIXON FRD	CEMENTATION CO. MATERIAL	OVER 500	10 - 80	25 - 360	NO	NO

* - A material which must be handled using safety precautions and/or protective clothing.
** - Pollutant to fresh water supplies contacted.
*** - Also available from grouting companies under trade names of PWG or Injectite-Q.

Watertightness is the ability of the grout to withstand the passage of water through the gelled grout. A grout must be practically impermeable to be useful in water shut-off applications. This quality should be given as part of the specification by the chemical manufacturer. Specifications should also state if the grout is subject to syneresis. This is the "squeezing" of water from a gel with time under the application of gravitational forces. It is desirable that a grout not be subject to syneresis.

Toxicity of the grout is important when the grouting is in the vicinity of a reservoir or where a groundwater supply might be contacted by the grout. Some grouts are toxic to the skin or by inhalation. These should be so identified on the manufacturer's specifications. The use of the grout should be governed by the grouting job location. Table 4 identifies the toxicity and pollutant qualities of many known grouts. If safety precautions are observed, the toxicity will not necessarily preclude their use.

4. Grout Strength

Grout strength is normally determined by laboratory tests. The grouts to be tested should be mixed and injected into a prepared soil sample from the site. An unconfined compressive strength test should be conducted on the grouted sample. There is no standard test for grouted soils, but the standard ASTM test for unconfined compressive strength of cohesive soils (ASTM D 2166-66) can be used. However, this test is for untreated cohesive soils, so a procedure is attached as Exhibit 1-A of the Appendix which outlines how the sample should be grouted and tested. The flow rates of the grout through the soil at given pressures should be measured in the tests. Flow rates with water should also be made before and after grouting to determine the change in permeability resulting from the grouting.

Two samples should be tested with each grout. If the strength test results vary widely, a third sample should be tested. At least two strengths should be obtained that will be reasonably close together and give an average value which can be used as a basis for grout selection.

D. FINAL GROUT SELECTION

The results obtained in laboratory tests should be evaluated to determine the best grout for the proposed job. The task is easy if one grout has sufficient strength to accomplish the job, and has low viscosity, satisfactory setting time, and less cost than the others considered.

On the other hand, if there are two grouts of sufficient strength with acceptable setting time, but one is considerably higher viscosity than the other, a decision will be difficult if the more viscous fluid is less expensive. (If the less viscous grout is also less expensive, this grout should be chosen). A thinner, more costly grout may prove to be the most economical since the time for grouting could be decreased, resulting in a cost saving for labor and equipment time.

It is difficult to calculate how the differences in the two grouts could be evaluated to select the best grout for the job. However, some comparison can be made by using the following equation (Darcy's radial flow equation) to give flow rates or grout take for the grouts being considered.

$$Q = \frac{(0.0316)\pi \; k \; h_t \; (P_w - P_e)}{N \; \ln\frac{r}{r_o}} \qquad (1)$$

where

Q = flow rate, gal/min

k = permeability, darcies

h_t = thickness of soil grouted, cm

P_w = wellbore pressure, atm

P_e = boundary pressure, atm (normally zero)

N = grout viscosity, cp

$\ln$ = natural log

r = radius of grouting, ft.

r_o = radius of injection pipe, ft.

Using equation 1, the example below illustrates how grout viscosity affects the flow rate and, proportionally, how it affects the time required for grouting.

Example 1:

The following values are assumed:

$k = 10^{-3}$ cm/sec (1.035 darcies)

h_t = 1 foot or 30.48 cm

P_w = 2 atmospheres

$P_e = 0$

$N = 1.5$ cp

$r = 2.5$ feet

$r_o = 1.5$ inches = 0.125 feet

$$Q = \frac{0.0316\pi\ (1.035)\ 30.48\ (2)}{1.5 \times 1.301} = 3.21 \text{ gpm}$$

If viscosity of grout is increased from 1.5 to 10,

$$Q = \frac{3.21 \text{ gpm} \times 1.5}{10} = 0.48 \text{ gpm}$$

Assuming no pressure increase and no decrease in grouting radius, the quantities of grout injected in 8 hours would be:

For 1.5 cp grout, Q = 3.21 x 60 x 8 = 1538 gallons

For 10 cp grout, Q = 0.48 x 60 x 8 = 230 gallons

If the job is of sufficient magnitude, the thinner, more expensive grout could possibly provide a lower overall job cost due to savings in labor costs. Therefore, the final grout selection between two acceptable grouts of different viscosities can be made by considering the economics for the entire job rather than just the grout material cost.

5. PLANNING THE GROUTING JOB

After the grout has been selected, plans can be made for conducting the job. The mechanics of a grouting job will be about the same regardless of the purpose: (1) to consolidate (or solidify) soil for excavation, (2) to develop a grout curtain or (3) to strengthen the soil for bearing purposes. The selected grout is injected into the pore spaces of the soil by pipes extending from the surface (if possible) in a regular pattern so that grout is placed throughout the job area.

A. INJECTION GRID PATTERN

For a typical grouting situation, pipes are placed into the soil formation in an appropriate pattern. The distance between pipes should permit the grout to travel at least half of the distance between pipes before setting to fill the pore spaces throughout the zone to be grouted.

Equations based on flow theory are helpful in preliminary planning; however, they are based on assumptions which generally limit their use beyond planning.

Equation 2 can be used to obtain the radius of grout penetration. This equation assumes injection at a point within an infinite, isotropic homogeneous mass. The rate of grout take, Q, can be obtained from the values determined in the calculations conducted in selecting the grout (see Equation 1). If the value of Q is too low to be realistic, a reasonable value of 3 to 5 gpm (11.36 to 18.93 lit/min) can be assumed. The choice of a setting time can be guided by the results of laboratory tests, but may be influenced even more by the ground conditions at the construction site. The setting time should be reduced where flowing groundwater is anticipated. The grout set should occur during injection to keep dilution to a minimum, and to force the grout into other channels or pore spaces to give broader coverage.

The spacing of injection holes should be somewhat less than 2r, where r is the grouting radius

$$r = 0.62 \sqrt[3]{\frac{Qt}{n}} \qquad (2)$$

where

r = radial distance of grout penetration, ft. (cm)

Q = rate of grout take, cfm (cu cm/min)

n = porosity of soil

t = pumping time or gelation time, minutes

1. Grouting from Ground Surface

A grid pattern is normally used when grouting is to be done from the surface for a grout curtain waterstop for consolidation of soil prior to excavation, or for strengthening soil under structures. A minimum of two rows of injection pipes can be used as shown in Figure 3. However, three rows are recommended as a minimum, except for very small areas. The center row should be offset equally between the holes in the other two rows. Wide zones, of course, will require additional rows, as shown in Figure 14. The distance between the rows and between holes in each row can be set at approximately 2r, based on the distance calculated by Equation 2, or based on prior experience. The spacing between holes and rows shown in Figure 14 should give complete overlap of grout as indicated by grout pattern.

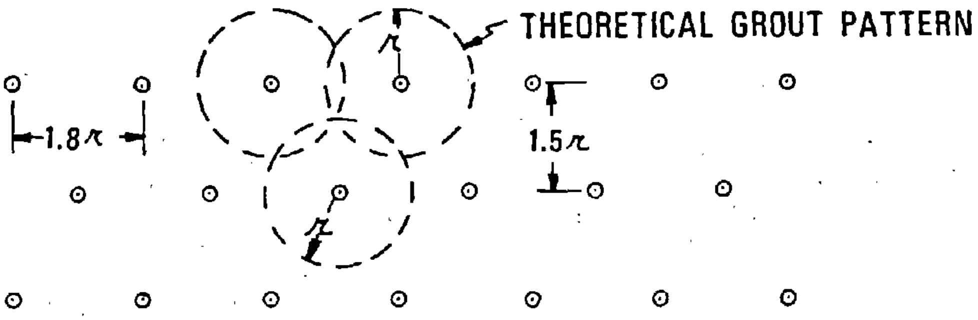
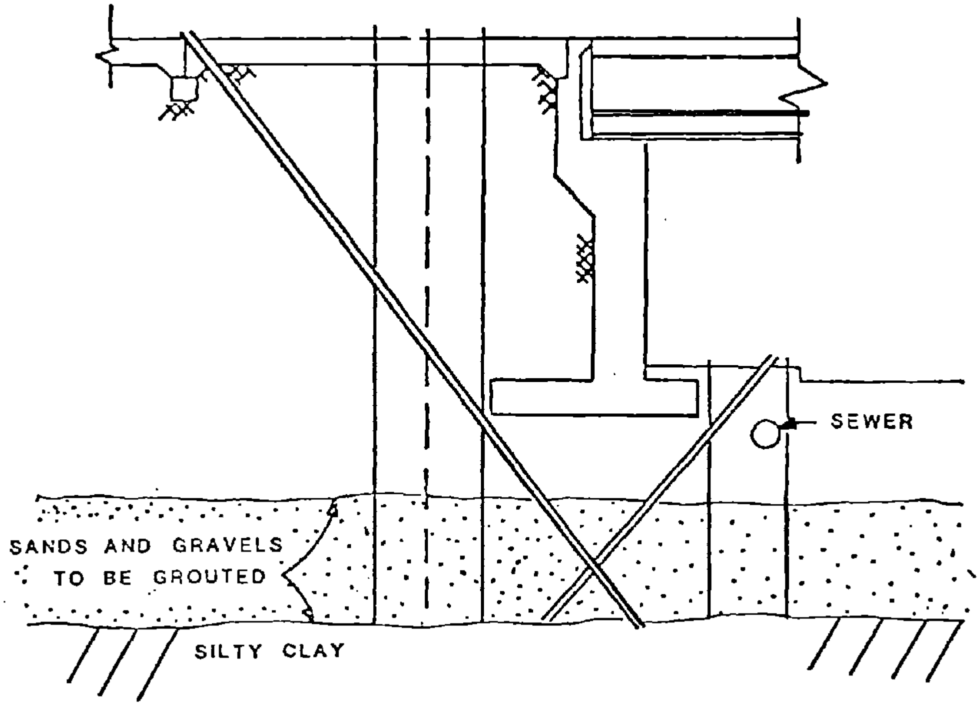


Figure 14. Injection pattern for ground surface injection

After the pipe spacing has been determined, the flow rate can be checked by Equation 1. If the rate is too low for economical operation, pipe spacing or pressure should be adjusted to obtain the desired flow rate.

Grouting can be done from the ground surface under structures to strengthen the soil for support when excavation is to be made adjacent to the structure or beneath the structure. The pipes are placed angularly as shown in Figure 15. The pipes should be spaced close enough to permit interlapping of the grout in the soil pore space.



COURTESY OF HAYWARD BAKER CO.

Figure 15. Injection from ground under adjacent structures

2. Grouting From Shaft, Cellar or Gallery

If grouting cannot be done from the ground surface, it can be done from either a shaft or a cellar. Grout pipes should be placed radially from the shaft so that the spacing at the injection zone is right. Figure 16 shows a sketch of a job using this type of injection system.

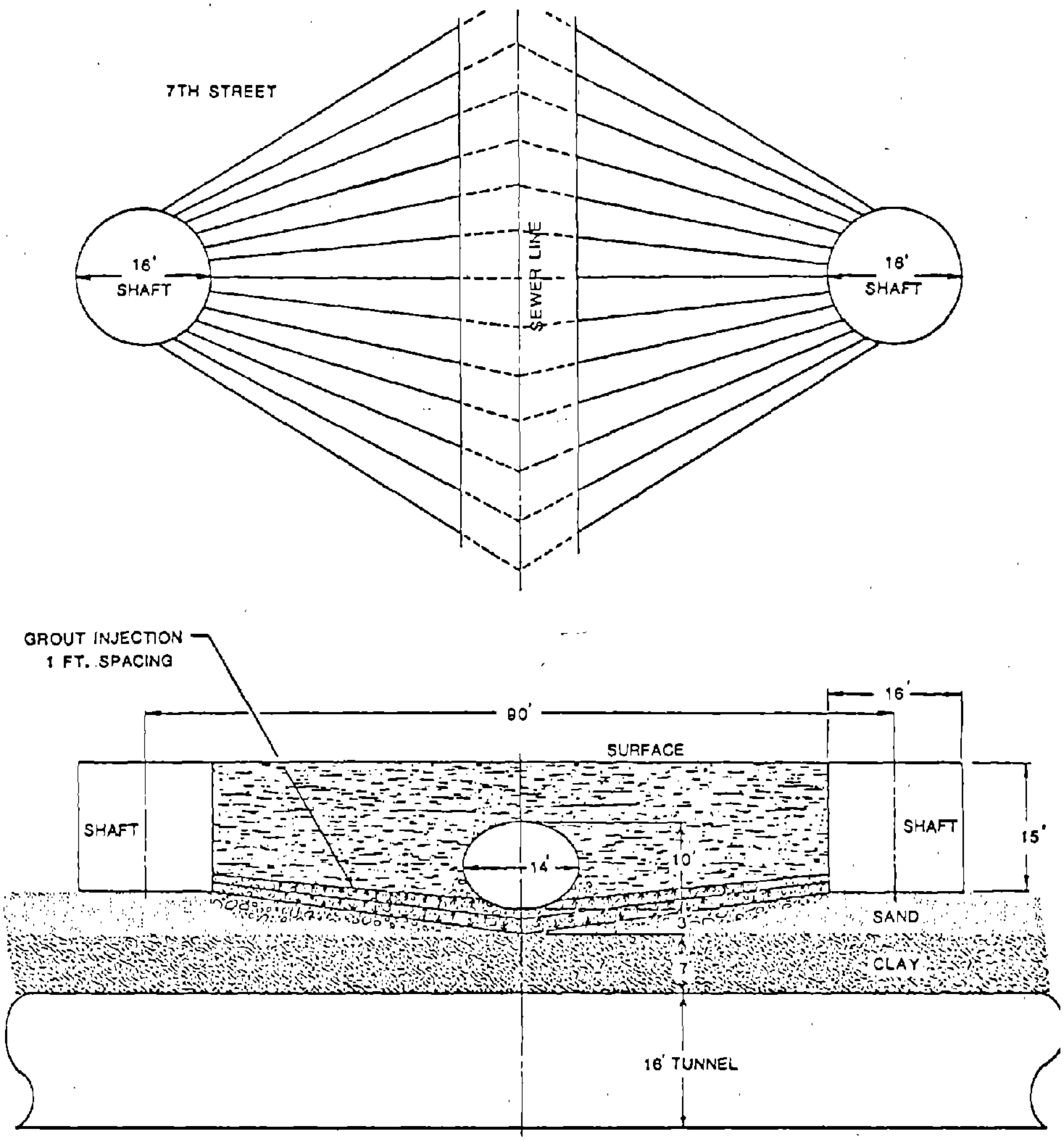


Figure 16. Grouting radially from shaft.

3. Grouting the Tunnel Face

When a tunnel is being dug behind a shield, injection can be made into the tunnel face ahead of the excavation to consolidate the soil and prevent loss of ground. In this type of grouting, pipes are normally placed in 2 or 3 rows around the circumference of the tunnel face. Figure 17 shows this type of pattern. Pipes are usually driven in about 15 to 25 feet (4.5 to 7.5 meters) then grouted in stages as pipes are withdrawn. Excavation is made to within 5 feet (1.5 m) of the end of the grouted section, and then more grouting is done.

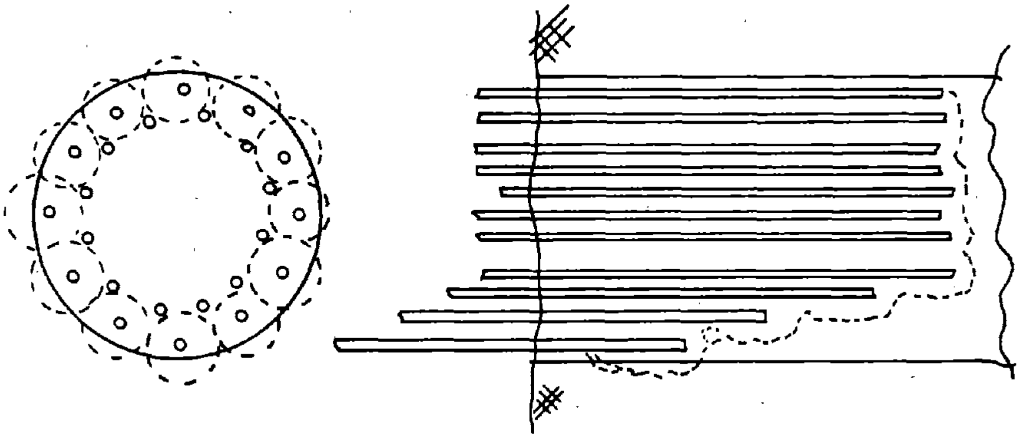


Figure 17. Injection pattern for tunnel face grouting

Pipe spacing patterns should be similar to those placed from the surface. The same equations may be used in planning pipe spacing and flow rates.

B. DOWNHOLE EQUIPMENT

The injection pipe selected for use on a grouting job varies from one contractor to another. However, some grouting specialists use the same type of pipe for all jobs because their equipment is suited for placement of that particular type, and their experience has largely been with that type. The various injection pipes being used are shown in Table 5. The predominate systems used in the United States have been the drive rod type and slotted plastic pipe. The Tube a' Manchette are used extensively in Europe.

The drive rods are steel injection pipes which are normally EW drill rod or equivalent. The lower element contains an expendable or moveable point for driving into the ground without plugging the

Table 5. Types of injection pipes.

NAME	DESCRIPTION	PLACEMENT	ADVANTAGES	LIMITATIONS
A. Drive Rod (Lances)	EW Rod with special pointed end or extrudable plug.	Driven in ground	Pipe retrieved. Can grout in zones or stages.	For depths to about 50 feet. Requires driving equipment
B. Slotted Pipe	Plastic pipe with slots.	Set in borehole w/gravel & grout.	No special equipment required	Can grout only one zone.
C. Tube à Manchette (See Fig. 18)	Plastic pipe with sleeve covered holes at given intervals (French origin, available in Europe).	Set in borehole with weak grout. Uses inner pipe with packers to straddle holes.	Can grout selectively and regrout as desired.	May not be available in the United States
D. Lost Injection Element	Single section element with sleeve covered holes (Netherlands)	By special steel tube with small plastic hose to surface. Element is left in ground.	Simple if contractor has equipment required.	May not be available in U.S. Special placement vibrator crane is required. Can only grout one section about 1 meter thick.
E. Open Hole With Packer	Uses cased hole with air packer set in end of casing above zone to be grouted.	In borehole.	Can stage grout as desired.	Requires packer and air source.
F. Stabilator Valve Tube	Steel drilling system also used for grouting (Swedish).	Drills with pipe, then knocks off bit and uses pipe for grouting.	Can grout selectively.	May be hard to obtain in the United States.

rod. Additional lengths of rod are added as it is driven to the desired depths. Injection of grout is normally made as the rod is withdrawn in predetermined stages. It is not normally used to grout below depths of about 50 feet (15 meters).

Plastic (PVC) pipe, normally 1 1/2 inch (38 mm) size, is used in a 3 to 4 inch (76.2 to 101.6 mm) borehole. The lower portion of the pipe is slotted with an electric saw over an interval corresponding to the section to be grouted, and surrounded by gravel or coarse sand in the slotted portion. Above the slotted portion, a cement grout is placed around the pipe up to about 1 foot (30.48 cm) below the ground surface. This pipe is a standard pipe and generally available in most localities.

The Tube a' Manchette system (shown in Figure 18) is composed of plastic sections about 18 inches (45 cm) long with one row of four 1/2-inch (12.7 mm) holes transverse to the pipe. The holes are in the middle of the section 90° apart and are covered by a rubber sleeve (or manchette). As many sections as needed can be screwed to the lower end of a plastic pipe to give the desired depth.

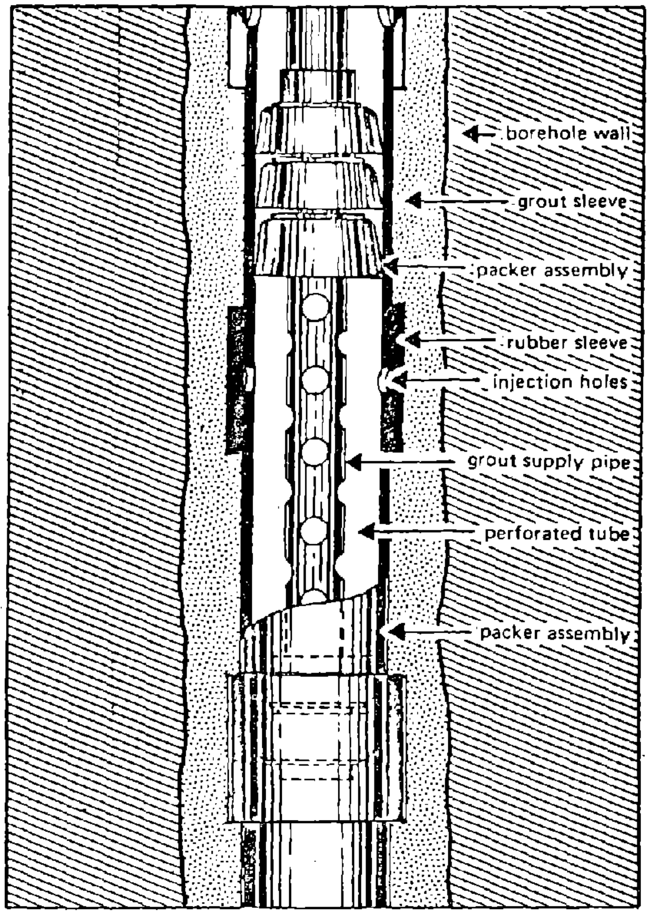


Figure 18. Tube a' Manchette

To grout through the designated section, the inner grouting pipe with two packers and a perforated section is inserted into the tube a' manchette section. Grout is pumped under pressure down the grout pipe into the isolated section between packers; the grout then flows into the 1/2-inch holes in the tube a' manchette, expanding the rubber sleeve which allows the grout to flow out into the desired zone of soil. Release of the pressure permits the sleeve to close and seal the hole. The grouting pipe can then be moved to the next section of tube a'manchette for additional grouting. The lost injection element is simply one special tube a'manchette section placed at a given depth for a one layer injection. This special procedure was related to only one company in Europe.

Two sizes of air inflatable packers are available for grouting in boreholes (Item E, Table 5). These are listed by Halliburton Services as 1-3/4" (44.45 mm) and 3-1/2" (88.9 mm) sizes. The 1-3/4" packer can be used in open holes from 2 inches (50.8 mm) to 3-1/2 inches (88.9 mm) in diameter. The larger packer can be used in boreholes from 3-3/4 inches (95.25 mm) to 5 inches (127 mm) in diameter. Both packers are expanded by air pressure, so an air hose must be run in the hole to the packer. A source of air or other inert gas with 100 psi pressure must be available on the site.

When packers are used, the maximum grouting pressure should be kept at least 5 psi (0.345 bars) below the packer inflation pressure. Grouting pressure should also be gauged by the vertical soil pressure in the zone being grouted to prevent uplift and possible fracture of the ground during grouting. The maximum inflation pressure for the smaller packer ranges from 100 psi (6.9 bars) in a 2-inch (50.8 mm) hole to 75 psi (5.18 bars) in the 3-1/2 inch (88.9 mm) hole; inflation pressures for the larger packer ranges from 75 psi in the 3-3/4 inch (95.25 mm) hole to 50 psi (3.45 bars) in a 5-inch hole.

The stabilization valve tube is used in the drilling of the holes, then the bit is "knocked off" and the pipe is used for grouting. The pipe contains holes similar to those in the tube a' manchette system, except the holes are covered by a steel spring rather than a rubber sleeve. Grouting is conducted by use of an inner grout pipe as in the tube a' manchette system.

The type of system to be used should be selected in the job planning, so the supporting equipment to place the pipe can be obtained.

C. PUMPING PROCEDURES

1. Mixing and Pumping System

The systems used for mixing and pumping are normally designed and assembled by the grouting contractors. Although the elements (pumps, etc.) of the system are available from suppliers, the systems themselves are normally proprietary. Most contractors use either positive displacement or progressive cavity type pumps. In a batch mixing system, one pump should be used on one hole at a time. Most contractors use several pumps to speed up the grouting operation, with each pump connected to a different injection pipe. Three systems are used for mixing the grout materials. The most widely used system of mixing is the batch system. This is a relatively simple system where the components are mixed or proportioned into a single tank and then pumped into the ground. It has three limitations: (1) the entire batch must be injected before the set time of the grout expires, (2) set times are difficult to change during pumping, and (3) short set times cannot be handled easily. This is important when flowing water is present which could wash away or dilute the gel if set time is too long.

The second system is the two-stream, equal-volume method. This system uses two identical pumps of equal capacity to pump two components of the grout fluid through separate lines to a mixing head. Here they are mixed in equal quantities as they are injected into the ground. The use of short set times is not critical on this system.

The third system is similar to the two-stream method except that proportioning pumps (or variable speed pump drives) are used to give the desired quantity of each component.

In each case, the mixing tank (or tanks) should be equipped with a gauge to measure the amount of grout injected; or, alternately, a flow meter should be in the line to measure the fluid from each tank.

A schematic of the two-stream system is shown in Figure 19. The batch system would require only half as much equipment. For example, only tank and pump number 1 would be needed. The proportioning system would be as shown except for the inclusion of a variable transmission between the motor and each pump.

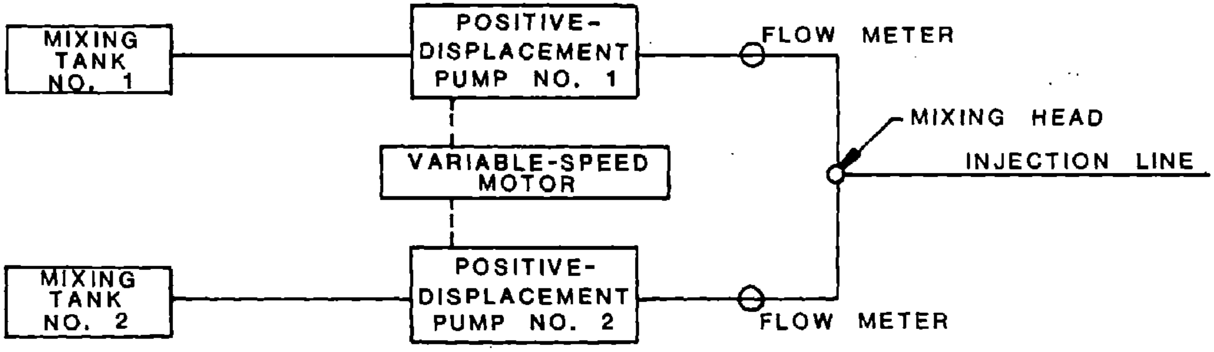


Figure 19. Two-stream pumping system

Facilities for storing and handling the grout components must be available for both liquid and dry sacked materials. For large jobs, the materials are generally obtained in bulk rather than in containers or sacks, and moved by conveyor screw or pump from large storage tanks into the mixer in the proper proportions. Tanks and related plumbing, other than for storage of water or silicate, should be constructed of noncorrosive materials that will not react with the chemical being used.

2. Injection Techniques

The injection techniques are basically the same for either drive rods or pipe set in a borehole. The amount of grout can be determined, once the thickness of the soil, pipe spacing and number of rows have been established for a particular job. Figure 20 shows grout volume required per foot of sand thickness for different porosity values. This information will then enable the contractor to determine the total amount of grout needed for a given job, and how much grout should be pumped at each interval as the pipes are withdrawn during the job.

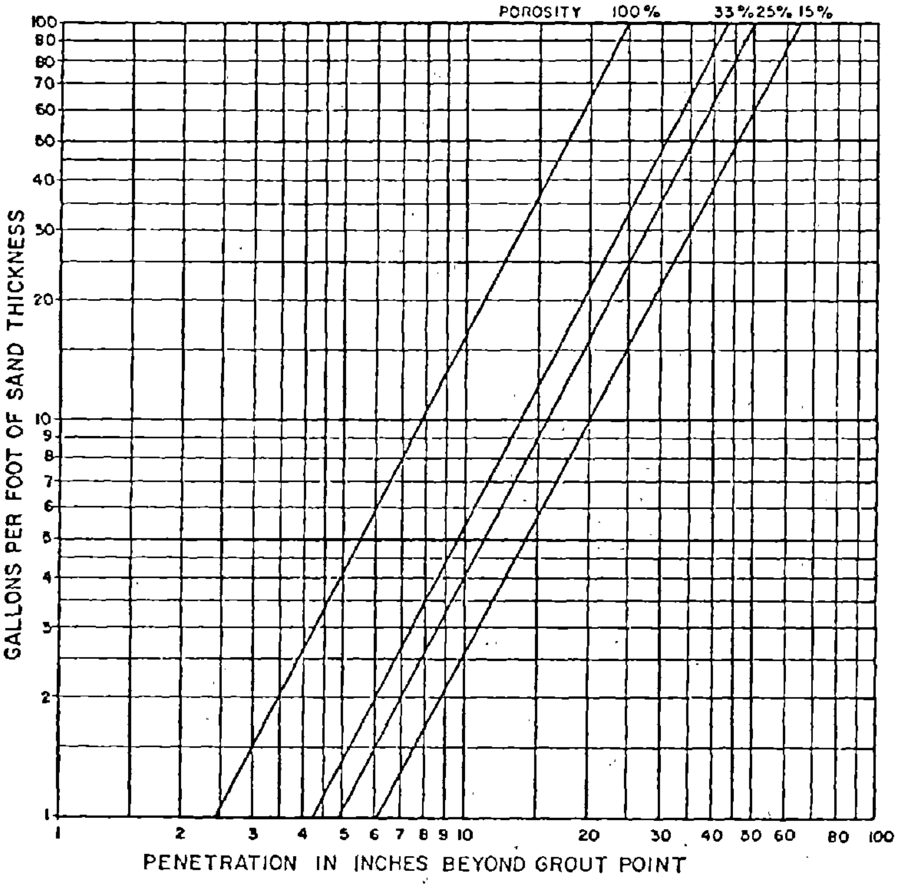


Figure 20. Grout volume required to fill radially around grout pipe

The flow rate, or grout take, depends upon the soil permeability, grout viscosity and pressure for each given grout radius. The time, in minutes, to pump the required amount of grout can be calculated by the equation below:

$$t = \frac{\text{Grout volume, gallons (from Fig. 20)}}{\text{Flow rate, gpm (from Equation 1)}} \qquad (3)$$

From Example 1, Chapter 4, with a radius of 2.5 feet and an assumed porosity of 33-1/3%, the grout required to fill the voids in a one-foot layer would be 47.5 gallons. Using equation 3 and flow rate from example 1,

$$t = \frac{47.5}{3.21} = 14.8 \text{ minutes (for a grout with 1.5 cp viscosity) or}$$

$$t = \frac{47.5}{0.48} = 99 \text{ minutes for a grout with 10 cp viscosity}$$

The time of injection found for this example seems excessive, so some adjustment can be made. If the injection can be made at a higher pressure, or with a lower viscosity grout, the time of injection will be less. If neither of these alternatives are available, the radius of grouting could be reduced to 1.5 or 2 feet and the time recalculated to see how this reduction in time will reduce the overall cost.

Injection patterns should be drawn with the rows identified with letters, and the holes numbered. A log, or some similar system, should be kept to record data from the injections made during the field operation. Space in the log should be provided for every stage planned for each hole; space should also be left to record the pressure used and the gallons pumped into each stage. If more than one grout is used, separate logs should be kept for each grout injected.

6. FIELD OPERATIONS

A. PREPARATION OF SITE

Holes should be drilled or grout rods driven in accordance with the planned injection pattern. If boreholes are used, the pipe should be set in place using the selected technique, and gravel or sleeve grout placed as required.

The tanks for storage of grout components should be placed in a location convenient to that selected for the pumping and mixing equipment. Storage tanks should be adequate for water and chemicals. The size of the mixing tanks is dictated by the job requirements. Figure 21 illustrates a typical job layout using equal volume pumps for the two-stream mixing method. If the batch or proportioning system is used, the layout would be similar except for the pumps and tanks.

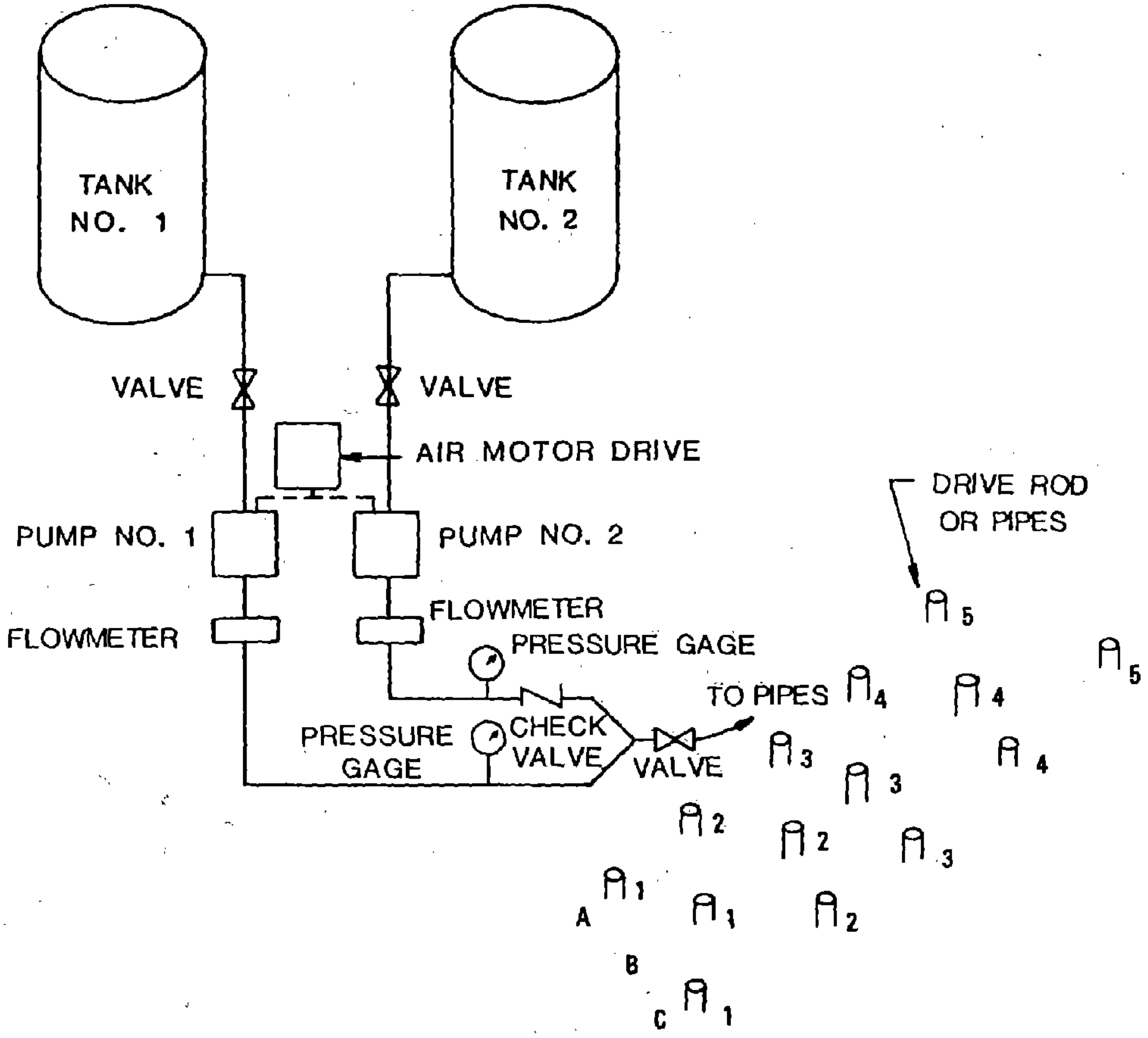


Figure 21. Schematic of job layout

The necessary injection piping should be on hand. Accessory equipment, such as smaller calibrated tanks or flow meters, should be installed to measure the grout used. Pressure gauges or recorders should be installed where they can be seen easily by the pump operator; however, if the pumps are very far from the injection pipe, more accurate injection pressure can be obtained from a gauge at the top of the injection pipe.

A standard penetration test using a split-barrel sampler could be made in several parts of the area to be grouted for comparative purposes after the grouting, if this was not done as a part of the site investigation.

B. GROUT INJECTION

1. Cement Grouts

If a cement grout is used, it should be mixed in proper proportions and injected. Precautions should be taken to hold the injection pressure below a figure of 1 psi per foot of overburden depth (0.226 bars/meter) to prevent fracturing and uplift. The pressure and the amount of grout used at each stage should be recorded on the grouting log sheet.

Injection should be made at alternate holes (1, 3, 5, etc.) in Row A. In addition, injection should be made at all stages in each hole before grouting is begun in the next hole. Figure 22 shows this operation for one typical hole with a drive rod; the procedure would be similar for any of the systems which permit stage grouting. While holes 1 and 3 are being grouted, hole 2 should be observed for water displacement or for grout coming from the hole.

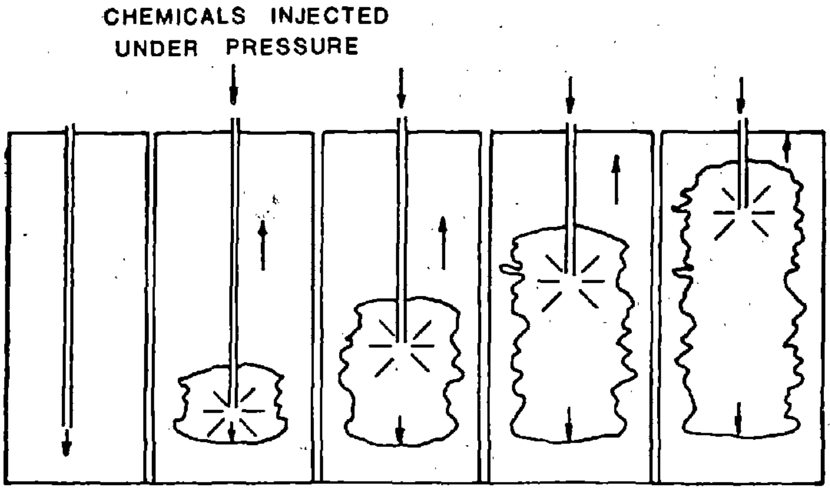


Figure 22. Grout technique by stages in one hole

After the grouting is completed in Row A on every other hole, the procedure should be repeated in Row C. The next step would be to grout the holes left in Rows A and C; the holes in Row B could then be grouted in sequence to complete the job.

2. Chemical Grouts

It is of utmost importance that the chemical grout should be mixed in the proper proportions. For a batch system, the mixed grout is moved to the injection tank, and then into the pipe and ground. For a two-stream system, the pumps take the fluid components from two separate mixing tanks to inject into the soil. The same procedure of injecting into alternate pipes should be followed as previously outlined for both first stage grout and final grouting in order to insure complete penetration.

If several pumps are used, grouting can be started in Row C after grouting has progressed for a number of holes in Row A. This will speed up the grouting considerably.

Based on information gained from the tests conducted during the site investigation, several variations in technique may be required. If existing groundwater has a low pH, a preflush of clear water should be used ahead of grout injection if a silicate or urea-formaldehyde grout is used. The presence of sulfides in the groundwater would require a preflush of ammonium hydroxide prior to using AM-9 or an acrylamide grout.

C. CONTROL AND MONITORING

It is very important that the grout injection process be constantly controlled and that records are maintained from the beginning to the end of the job. Since the treatment is underground, the results or degree of success cannot be known with certainty until after grouting is completed, and some type of test or excavation is made in the grouted area.

Quality control of the treatment during the course of work requires constant monitoring of the grout components to verify correct mixing, proper injection pressures, desired flow rates and total quantity of grout injected at each stage. Records should be kept on a log sheet during the grouting operation. Headings for a typical log sheet are shown in Figure 23. The injection pressures and rate of injection should not be permitted to exceed that established for the job from the soil characteristics. Samples should be taken of the final grout solution to check the set time.

GROUTING LOG SHEET

Date: ____________________

Gen. Contractor: ______________________________ Location: ____________________

Type of Work: ______________________________ Grout Type: ____________________

Gel Time (Sample): ________________ Ground Elevation: ______________________________

Hole No.	Stage	Depth	Injection Pressure				Quantity Injected	Inj. Time	Average Inj. Rate	Grout Holes	
			Initial	Final	Max.	Avg.				Slope	Direction

Figure 23. Typical grouting job log sheet.

7. FIELD VERIFICATION OF COMPLETED GROUT TREATMENT

A. SPECIFICATION REQUIREMENTS

Depending upon the specifications, the contractor may have to establish proof of the success of grouting. This may be in the form of reduced permeability, or the attainment of a specified unconfined compressive strength, a change in soil resistance, or the injection of a certain volume of fluid at a given pressure. This requirement should be known before the job is started.

B. SAMPLING AND TESTING GROUTED SOIL

Obtaining soil samples from the grouted soil may be difficult with conventional samplers and methods. If a conventional split-barrel sampler will not work in the grouted soil, it might be necessary to use a rotary drilling unit to obtain a core for laboratory test samples. If the soil is cemented sufficiently with grout, it may stay together well enough to use this method.

When suitable samples cannot be obtained with a sampler, it will be necessary to dig a test pit down to the grouted depth with a sufficiently large hole to permit samples to be retrieved by hand for laboratory tests.

For the samples that are retrieved, tests should be made as outlined in ASTM D-2166-66 to obtain the unconfined compressive strength.

C. IN SITU TESTING

1. Permeability Tests

Permeability tests are probably the simplest way of confirming a successful grouting job. Tests may be conducted in the same holes tested before grouting to determine the change in permeability. It might be more conclusive to drill a hole at random between several injection holes to determine if grout penetrated thoroughly throughout the soil. The same type of tests (constant head or falling head) which were used before the grouting should be repeated. The reduction in permeability obtained by this test would be an excellent measure of the grouting success.

2. Strength Tests

Strength tests before and after grouting would provide a direct comparison of the change in the soil strength. The test of the soil resistance after grouting might be measured with the standard penetration test. The Menard pressurementer and the Iowa Borehole Direct-Shear test device are two other in situ testing tools which may be useful to obtain a shear strength of the grouted soil.

D. PERFORMANCE TESTS

The most commonly used and most accurate method for evaluating a grouting job is full-scale performance. This is particularly true for grouting to consolidate the soil for tunneling. Ease in excavation quickly proves whether the grouting was effective or not.

Performance of grouting to underpin a building foundation could be determined by the amount of settlement occurring during nearby excavation. Settlement of any significant amount, however, cannot be tolerated. Therefore, the structures should be monitored during excavation to detect any movement that occurs, so that immediate action can be taken to prevent further movement before damage occurs to the structure.

E. WRITTEN DOCUMENTATION OF THE GROUTING JOB

As noted previously, a log should be kept of the detailed data of the field operation. This information should then be incorporated into a report to the general contractor and/or owner covering the work done, equipment used, procedures followed, and material used. This report would become a permanent part of the project documents. Publication of such reports as papers or magazine articles would be of great value to the underground construction industry. It would serve to broaden the knowledge of grouting among designers and construction personnel as well as the grouting specialists.

8. THE DESIGN PROCESS, SPECIFICATIONS AND CONTRACTS

Previous chapters have dealt with typical grouting applications, site investigations, grout selection, grout job planning, field operations and field verification of results. This chapter examines the design engineer's responsibilities in preparation of drawings and specifications, and the way such documents should be prepared. A brief discussion of contractual arrangements and responsibilities is also included.

A. RESPONSIBILITIES OF DESIGNERS AND CONTRACTORS

Some grouting plans originate in the office of the responsible designer, but others are developed by the contractor. It is the responsibility of the designer to determine the extent that a grouting operation should be designed, or even whether grouting should be anticipated and provided for in the contract documents.

There is no doubt that the best grouting expertise lies with the specialist grouting subcontractor, and many decisions are properly allocated to him. It must also be realized that most general contractors have little or no expertise in grouting. Many designers are equally uninformed, but they cannot dodge the issue; they must provide the proper information and contract documents for a satisfactory grouting job.

The design details provided by the designer depend largely on (a) the extent to which grouting will affect the final structure and adjacent property, and (b) the relative economic importance of any grouting to be done. Several applications may be considered using this criteria to determine the design responsibility in each case:

1. Construction where grouting forms a permanent part of the final structure. (Examples: Grouting to strengthen soil under new footings; grouting for permanent water cut-off).

2. Grouting as an integral part of the construction method. (Example: Backfilling of tail void).

3. Grouting to provide permanent protection of adjacent property. (Example: Grouting to strengthen existing foundation soils to transfer the load to a lower, incompressible stratum).

4. Grouting which provides temporary protection of adjacent structure, or temporary stabilization of tunnel face or excavation. (Examples: Grouting to minimize ground loss in running soil; grouting for temporary water cut-off).

5. Grouting as an alternative construction expedient. (Examples: Preplanned optional local or large-scale water cut-off; optional soil stabilization or ground loss prevention).

6. Grouting as an emergency measure to neutralize an unexpected subsurface condition that causes unforseen construction difficulties. (Example: Grouting to stop excessive local water flow or soil instability).

7. Grouting as a remedial or repair measure. (Example: Grouting for leaks in final structure).

In the first three cases, whether grouting is selected as the only solution or as an alternate, there is no doubt that the designer must provide drawings and specifications as complete as practical. In the fourth case, and sometimes the fifth, complete design details must also be provided whenever the temporary protection or stabilization is critical and when grouting is counted on as a definite protective measure, for example, in lieu of underpinning.

In the fifth case, where grouting is entirely a contractor option, some of the detail can be left out of the design documents; however, the desired results must be expressed in such terms that the general contractor can determine the best method for accomplishing the results in the most expeditious and economical manner. Sufficient data must be included to enable the contractor and his subcontractor to determine groutability and plan the grouting.

Grouting as an emergency measure is not really a subject for design, except to include basic soil data from the site investigation. However, in certain critical instances where distress due to an inadvertent loss of stability must be avoided, it is possible to prescribe the constant availability of emergency grouting equipment and crew.

When a designer specifies a grouting program as the single solution to a problem, he is responsible for the following:

1. Determining soil groutability.

2. Providing major design components (tentative grout selection, drawings, specifications, job controls).

3. Providing data for planning and conducting the grouting operation.

If grouting is indicated only as an approved alternative, the designer still has the responsibility to furnish enough basic soil data and minimum requirements to premit the contractor to evaluate the grouting alternate. Though the basic responsibility for design, planning and conducting the grouting operation usually lies with the general contractor, he may well select to delegate this responsibility to the subcontractor. The responsibility should be clearly delineated in the contract documents, which will be discussed later.

Grouting as an emergency measure is usually the contractor's responsibility, except that specifications may require standby equipment and crew under critical conditions. Some restrictions on the extent of grouting and maximum grouting pressures may be imposed.

Repair grouting is not ordinarily a design item, unless under special contract. A typical example would be to simply require the grouting contractor to deliver a final product that does not leak.

The following discussion of the basic ingredients of a grouting job design will further clarify the delegation of duties and responsibilities.

B. DESIGN DRAWINGS AND PERTINENT DATA

Although proper specifications are probably more important than any other design item, the design drawings and the presentation of pertinent data are also necessary. Presented here are the requirements for a reasonably complete design; items may be abbreviated or eliminated when a shift of responsibilities to the contractor is appropriate.

As a basic minimum, the following types of drawings must be prepared:

1. Drawings showing the general intent, and the minimum geometrical extent of grouted soil. These drawings must also show all structures, foundations and utilities. Notes must indicate the known accuracy of utilities and existing structure data.
2. Drawings showing all space restrictions, restricted overhead, available contractor's working area, etc.
3. Drawings showing all exploratory boring data and other geotechnical data available for the vicinity, including all known groundwater data.

In addition, representative test data from field and laboratory tests must be procured and presented in the contract documents to allow the contractor to select, design and execute all grouting details. These data should include:

a. Grain size distribution.

b. Laboratory permeability

c. Soil porosity

d. Laboratory groutability

e. Permeability and unconfined compressive strength of grouted soil sample

f. Chemical tests on soil and groundwater

g. In situ permeability

h. In situ density and/or deformation modulus

i. N values, pressuremeter data, or any other similar data procured

j. In situ pumping test data of tentative grout (if desired)

k. Any indications of moving groundwater

These data, together with all logs available on the subject area, should be certified as to their accuracy, and any technical appraisals of groutability carried out by the designer must be presented. The final appraisal of all data, however, must rest with the contractor since he will be responsible for the execution and detailed design of the program.

As a rule, it is not necessary for the designer to indicate on the drawings the detailed layout of the grout holes, or the sequence of grouting; this will usually be done by the contractor. In many cases, the designer will prescribe a minimum number of rows for grout holes, and sometimes also establish a maximum spacing. He may prescribe grouting procedure, or simply that short gel times be used first and longer times later.

C. SPECIFICATIONS

The detailed contents of specifications will depend greatly on the purposes and details of the grouting, the criticalness of quality and work control and the type of grout specified or allowed.

Three basically different types of specifications may be set forth:

1. General performance specifications, in which only the performance of the final product is specified without intermediate controls.

2. Specific performance specifications, in which intermediate controls are also incorporated.

3. Execution specifications, in which all significant details of the grouting scheme are spelled out, or, it is basically designed completely by the design engineer.

General performance specifications have three main advantages: (a) they can be written by people with limited knowledge of grouting, (b) they take full advantage of the grouting contractor's special expertise, or (3) they theoretically are directed toward the real goal of the grouting job - the desired performance. Conversely, this type of specification has three weak points. First, the grouting contractor has generally finished his job and left the site long before the performance can be evaluated; second, nonperformance can result in unchecked adverse conditions before remedial measures can be undertaken; and third, such grouting specifications can be carelessly written without a thorough examination of the overall feasibility and possible pitfalls.

Complete execution specifications could theoretically be written so that a novice grouting contractor could perform the job satisfactorily. This is also dangerous and often not economical because subsurface conditions are seldom known before excation. Every grouting job must go through experimental and testing phases by which the ideosyncrasies of a particular site are studied and the finer details of the grouting scheme modified. In grouting work, one must rely a great deal on the grouting specialist's experience and ingenuity; specifications that are too strict may hamper his efficiency.

For most significant grouting jobs, an ideal compromise specification must be written to assure full cooperation with the best effort on the part of the grouting contractor, the best possible final performance, controls of the job before the grouting job is finished and delivered, an equitable price to the owner and an equitable remuneration to the contractor. It should also provide for the safety of the workers and for protection of the adjacent environment.

The following items should be included in the specifications, roughly in the order in which they might appear. Greater or lesser detail than shown here may be included, depending on the conditions. This guide applies specifically to a job using chemical grouts; it would require some modifications for a job using cement grout and for compaction grouting or remedial grouting.

1. <u>Scope of Work</u>

Brief statement identifying the type and location of work.

2. General

a. Work to be included: All supervision, labor, materials and plant; all operations and equipment to drill and support all necessary holes; all grouting chemicals and other supplies; all operations and equipment to supply, transport, store, mix and pump grout materials; and all testing and evaluation as specified. Also, statement of basic purposes and goals of grouting plan with reference to drawings.

b. Work not to be included: Any material or equipment that may be available on site (e.g. site office), any testing or monitoring to be done by others.

c. Responsibilities: The duties and responsibilities of the contractor and of the engineer (owner's representative). All grouting plans and changes are to be submitted to engineer for review. The definition of nonperformance and the consequences of nonperformance.

d. Working requirements: The definition of space restrictions, working hour restrictions, traffic interference, and other restrictions. Provisions for flagman, policeman, barricades, flashers, etc. References to drawings showing available working areas and existing structures or utilities on the site that may interfere with or be affected by grouting operations.

3. Materials

Basic grout types allowed or excluded by chemical description and, if desired, by commercial name. (Note: All materials to be delivered to the site in undamaged,unopened containers bearing the manufacturer's original label).

a. Basic requirements: Maximum concentration required and/or minimum allowed (lbs. per gallon of water); range of viscosities allowed (centipoises); ability to withstand dilution by groundwater of at least 50% by volume without significantly affecting gelation while at rest or in motion; groundwater pH tolerance range (pH range expected:________); reaction to be controllable from ______seconds (minutes) to______minutes (hours) at ground temperatures from ______ to ______.

Catalyst ,activator, inhibitor, buffer, soluble additives to be in accordance with basic requirements, and all fully compatible and tested if necessary. Compatibility to be demonstrated to the engineer's satisfaction.

b. Dye tracers: May or shall be used. Compatibility to be demonstrated to the engineer's satisfaction.

c. Insoluble additives: May be added as fillers or for other purposes, subject to approval and demonstration of compatibility and pumpability of mix. (Note: Infiltration of toxic materials into groundwater in significant quantities is usually not allowed).

4. Handling and Storage of Materials

All materials shall be transported, stored and placed in the manner prescribed by the manufacturers of those materials, as detailed in published data provided by the manufacturer. Spills must be cleaned up and washed with water (or solvent if required) and wasted or spilled material must be disposed of with due consideration to the toxicity of the material. Protective gloves, goggles, masks or other equipment must be worn in accordance with manufacturer's recommendations. (Note: Some fumes are toxic and ventilation may be required in close quarters. Some grouts (e.g. formaldehyde) give off noxious fumes when later exposed; such constituents may be limited or prohibited for certain tunnel work).

5. Equipment

The equipment used for mixing and pumping of chemical solutions shall be proportioning equipment designed for continuous injection (batching sometimes allowed when long gel times are anticipated). It shall be approved on site by the engineer prior to use.

a. Proportioning equipment: Shall fulfill the following minimum requirements:

The pumping unit shall consist of two pumps for the two-stream system and one pump for the batch system, with discharge not less than _________gpm (lit/min) at a pressure of _______psi (bars). (Specify the flow and pressure requirements). Multiple pump units may be used to decrease the grouting time. (Note: For coarse grained soils, it may be possible to pump at 10 gpm (3.78 lit/min) or more. For tight formations, pumping rates will probably be less than half this amount. Pumps cannot be expected to operate efficiently at less than 25% of their maximum rating. Therefore, do not specify larger pumping rates than are actually needed, or the equipment will not be effective at low pumping rates).

The arrangement of the pumps and the drive systems shall be such that the pumping rate can be varied between _______gpm (lit/min) and maximum volume without changing the ratio of the components in the grout formula. (Notes: Specify here the minimum anticipated pumping rate. If this value is less than 25% of the previously specified maximum, it may not be possible to cover the full volume range with one pump unit. It shall also be possible to vary the induction period without changing the total volume pumped. Both of these procedures shall be possible while the pumps are in operation).

The pumping unit shall be equipped with a manually adjustable relief system which shuts off the main power source at any preset pressure. The pressure range shall be such as to permit operation at any point over the full pressure range of the pumps.

Each pump shall be equipped with either flow meters to measure grout injected, or tachometers that can be calibrated in terms of grout volume injected.

Each pump shall be equipped with accurate pressure gauges. Additional pressure gauges shall be installed where directed. (Note: Where long lengths or hose are used to convey the grout solutions, it may be desirable to place a gauge at the soil face or top of the injection pipe to obtain a more accurate measure of the injection pressure.

The pumps shall be equipped with hoses of adequate capacity to carry the grout and activating solutions separately to the point where they are pumped into the ground.

The hoses shall come together in a "Y" fitting with check valves to prevent backflow in the hoses, and a sample cock beyond the point where the chemicals are mixed.

Pumping of the grout through a manifold to a maximim of ______ grout holes will be allowed, provided uniform flow into all holes is assured through metering and control valves or through automatic flow control valves, and provided the grout is measured through each individual line.

All operating components of the grout plant shall be made of materials compatible with the chemicals to be handled.

Separate mixing tanks or sets of tanks must be provided for each of the pumps. Capacity of these tanks shall permit continuous pumping at maximum capacity of the pumps during each separate injection. Small tanks are permissible, provided that two sets are available so that chemicals can be mixed in one set while grout is being pumped from another set. Tanks shall be made of materials compatible with the chemicals to be handled, and shall be provided with covers.

Packers, stuffing boxes, and pressure testers shall be provided for all sizes of grout holes to suit the specific site condition. All such equipment shall be approved by the engineer prior to use. (Note: Under cold weather conditions, it may be necessary to provide heated water for grout mixing in order to maintain proper control of the grout).

All components of the grouting equipment shall be in working order and in good repair, and shall be maintained in this condition throughout the job. Malfunctioning equipment or gauges shall be repaired or replaced before grouting begins or continues.

6. Supervision

Supervision of all grouting operations shall be the direct responsibility of a professional engineer or geologist (herein identified as the grouting engineer) previously experienced in the application of grouts (specific qualifications may be stated here). The grouting engineer's resume shall be submitted before he assumes any project responsibilities at the site, and the engineer reserves the right to disqualify persons with inadequate experience as grouting engineer. This may apply also to the grouting foreman. The grouting engineer shall have direct control over placement of injection holes, grout pipes, relief and observation holes, mixing of the chemicals, determination and adjustment of gel times. He shall also maintain complete records of the grouting operation. The grouting engineer or his foreman shall be present whenever grout is being placed. Safety and protective measures for all personnel involved with the grouting operation shall also be the direct responsibility of the grouting engineer. Grout mixtures and grouting procedures are subject to the approval of the owner or his engineer.

7. Application

The application of grout shall be under the direct supervision of the grouting engineer. Application shall be understood to include at least the following:

a. Placement of grout holes: Holes may be placed by rotary or percussion drilling, driving or jetting (using water or air), depending on the formation and its response to hole placement. (Note: On occasions, the use of water under pressure may cause excess pore-water pressures and cause soil instability, excessive ground movements, or other undesirable effects). Casing or other means for hole stabilization must be provided for caving formations.

Holes must be placed accurately and in an appropriate pattern to insure overlapping of grout from adjacent holes. (Note: State here if special types of grout holes or downhole equipment will be required such as regroutable holes (tube a' manchette), packers in perforated casing or any other desired feature. Many such features will increase the price, and should be justified).

Grout pipes, left in place in areas of planned excavation, shall be of a type that will not cause delay or difficulty in removal during excavation, e.g.,PVC pipe.

b. Grout pattern: The geometric layout of all holes, the sequence in which the holes are placed and grouted, and the vertical dimension and sequence of grouting the zones or stages for each hole shall be specified. The complete grout pattern shall be planned before start of hole placement and submitted for review (and approval) by the engineer.

c. Pumping or injection pressures: The pumping pressure at the collar of any hole shall not exceed _____ psi, except that transient overpressures up to _____ psi, not lasting over _____ seconds may be allowed. (Note: Overpressures of long duration may cause heave of soil and adjacent structures, or may cause fracturing of the soil rather than permeation. Fracturing is usually not desirable because it opens channels to receive the grout and it reduces the chances for a successful permeation of the desired soil).

d. Grouting concentration or mix: Specify general range, minimum allowed at any time, maximum expected. (Note: Strength requirements may indicate a higher than ordinary concentration; higher concentrations usually result in higher viscosity, and higher concentrations are also more expensive).

e. Compatibility of grout with soil and groundwater: If chemical content of soil or groundwater is not compatible with grout, special fluids used as a preflush may be necessary. The grouting specialist shall be responsible for making the necessary determinations for the type of preflush solution that will alter the subsurface conditions to be compatible with the grout.

8. Tests, Controls and Monitoring Observations

Include most or all of the following controls and tests:

a. Gel time and gel characteristics: A sampling cock placed between the "Y" fittings and the grout hole or pipe shall be used for obtaining samples to verify gel time prior to grouting, and for checking gel time and characteristics periodically during the job, or at least every _____ minutes during pumping times. (Note: Request the contractor to demonstrate by laboratory grouting tests, using site samples, that he can obtain the desired strength or permeability with his selected grout types and mixes. Soil tests would also be used for refinement of the detailed grouting design).

b. Field permeability tests: Determine relative permeability by water injection tests made in grout holes, or in holes especially drilled for the purpose, using clear, clean water at a pressure equivalent to typical grouting pressures. These tests shall be made before and after grouting injection, at the times, locations and elevations approved or designated by the engineer. Residual permeabilities after grouting shall show an acceptable reduction (for example, a 200 fold minimum) of permeability after grouting at all locations near the center or centerline of the grouting application.

c. Strength or modulus test: The soil strength after completion of grouting of each designated area (shown on drawings) shall be tested by standard penetration tests in an ordinary soil exploratory boring. Test results (number of blows) shall be at least doubled when comparing before and after results (not applicable in soils with gravel or soils which originally have over about 200 blows). Alternatively, testing can be specified by pressuremeter; tests shall show a minimum modulus or a minimum strength.

d. Coring: A minimum of ______ borings shall be made with ______diameter high-quality rotary type coring equipment. The core shall be examined for grout and shall be approved if satisfactory, by the engineer. Unconfined compressive strengths shall be made if possible.

e. General field observations: All grout penetration upward to the ground surface, through cracks or into utilities, basements, etc., shall be noted and recorded; if critical, in the engineers opinion, steps shall be taken to counter such grout loss. At critical locations (specify locations), heave measurements shall be made by taking elevation measurements before grouting and at appropriate times during and after grouting. (Note: In some cases, virtually constant monitoring of critical items may be specified for given time periods during grouting).

f. Monitoring of grout pressures and grout take: Grouting pressures and grout take shall be measured and analyzed as a running control of the grouting results. The grout take into each hole at each stage shall be carefully recorded, as well as the average and maximum pressure employed. The monitoring of secondary grout holes is particularly important for the evaluation of the whole grout job. Criteria for acceptable grout takes and pressures could be made part of the specifications, with additional grouting required if the criteria is not met. (Note: On large and critical jobs it may be desirable to specify the use of automatic recording devices, possibly for remote monitoring in a control room).

g. Site laboratory tests: When soil conditions vary significantly in the zone to be grouted, a complete grouting laboratory may be required at or near the site. This laboratory may, for example, continuously check the soil characteristics, pH values and chemical analysis of groundwater and other water used, ground and water temperatures, and air contents of liquids.

9. Stand-by Grouting Equipment

When the successful performance of a grouting job is critical, and it cannot be properly evaluated until actual excavation in the grouted zone, specify that grouting equipment, and materials be available at the site, and a grouting specialist be available in ______hours after call. Stand-by personnel and equipment may be required for only short stretches or short periods of work, which should be so indicated in the specifications.

10. Records

The contractor shall maintain complete and up-to-date records of his grouting and testing operations and make such records available to the engineer on demand. These records shall include at least the following items:

a. Hole number and stage number as identified on the contractor's approved plans and drawings.

b. Time and date of initiation and completion of grouting for each individual hole and lift.

c. Slope and direction of inclined grout holes.

d. Elevation (or depth) at which grout is injected.

e. Grout mix ratios, concentrations of base materials, reactants and any admixtures.

f. Pumping pressures, initial, average and final.

g. Grout take at recorded pressures and total for hole or lift.

h. Gel time as measured on sample from sample cock.

In addition, all records of any testing and monitoring specified herein shall be maintained carefully, completely and up-to-date.

11. Quantities

The work described herein and shown on drawings ________ is estimated to include the following approximate quantities:

Grout holes, uncased________linear feet or No.)
)
Grout holes, cased________linear feet or No.) Includes
)
Grout holes through structure________ No.) ________%
)
Grouting material injected:) for waste
)
Type________ Gallons________) or overage.
)
Type________ Gallons________)
)
Volume of grouted soil mass______cubic feet)

Field Tests:

Type________No.________

Laboratory Tests:

Type________No.________

Stand-by Time________hours/days/shifts

(Any other quantification that may aid the contractor in preparing his bid and his plans).

12. Payment

Many types of remuneration are possible, and the type specifically suited for a given job will depend on how well the job can be defined in advance, the complexity of the job, the soil conditions, and the degree of control exercised by the engineer.

For small, well-defined jobs, a lump-sum payment for the grouting job may be appropriate, but generally pay based upon amount of work should be used. The amount of work is normally related to units described under Quantities; however, not all units will necessarily be pay items.

Mobilization and demobilization may be covered in a lump-sum item, assuming that the plant size and number of pumping units, etc., are well defined. This item may also include such auxiliary costs as barricades and guards.

Field and laboratory tests and stand-by time should be paid for on a time basis. With this arrangement, the engineer may request any number of tests or hours of stand-by without penalizing the contractor and causing conflicts.

Items such as heave monitoring would usually be included in other units, but where such monitoring is critical, a unit price (e.g. survey crew hours) may be used so that the contractor will not be tempted to skimp on monitoring.

D. CONTRACTURAL ARRANGEMENTS AND DOCUMENTS

A contract to grout may be a quick verbal agreement between a contractor and a specialist subcontractor. Conversely, it may be a carefully conceived and formally executed document based on detailed design and complete specifications prepared by a design engineer. Both types, and combinations thereof, have their place in today's grouting world.

It is important for the success of the grouting, and for the resolution of contractural problems during construction, to decide early how detailed the design is to be and what format a possible contract should have. A specialist grouting contractor is often called upon to solve a serious groundwater or stability problem after the problem has caused some damage, and at a time when construction delay is inevitable. The specialist is asked to apply his expertise with little time to obtain any significant additional information on site conditions, or to weigh alternatives on grout selection. The distribution of responsibilities frequently is vague, and payment for services is sometimes undetermined at the outset, although more or less standard negotiated unit rates are often applied. Since the adverse condition in such instances comes as a surprise to the contractor, he would usually attempt to recover the costs of both the grouting program and any associated delays or encumbrances as an extra, due to "changed conditions." Because of this, contractors are not eager to disclose the contents and wording of the subcontracts for grouting services.

9. BACKPACKING, REMEDIAL GROUTING AND GROUTING OF ANCHORS

A. BACKPACKING TUNNEL LINERS

Backpack grouting in modern tunnel construction refers to filling the annular space between a tunnel bore and the tunnel liners (or rings) with a portland cement-sand slurry. The tunnel bore is somewhat larger than the outside diameter of the tunnel liners. The liners can then be put in place immediately after excavation of about four feet. The rings, typically about 3-1/4 feet long, are erected by bolting the sections together and to the last ring installed. Ring grouting is started immediately after the ring is in place. Most of the rings are cast iron or steel and contain plugged holes around the periphery through which grouting can be done. Grouting is accomplished using a slurry of sand and cement. A typical grout consists of about 65% sand, 20% cement and 15% water.

Backpack grouting should be accomplished as quickly as possible to fill the space behind the ring before the soil can fall into the space and cause settlement on the ground surface above. Hole plugs are removed and grout injection is begun at the bottom of the tunnel liner. The grouting progresses up the sides to the top. Injection points are moved up as the grout appears in the hole next higher up the side, or as it leaks into the tail of the shield. Pump pressure should be kept as low as possible to move the grout without danger of fracture. The grout should be mixed and ready for use as each section of liner is placed.

A final stage of grouting should be accomplished using a neat cement grout with one part of cement to one part of water by weight. This will be done after the initial stage has set to squeeze cement into any remaining voids.

B. LEAK REPAIRS IN CONCRETE STRUCTURES

Many concrete structures built below the groundwater level will leak. This is especially true in tunnel linings, basements or other similar structures. Leaks are often caused by cold (open) joints, cracks, penetration of wall by utility or other object, expansion joints, waterstop, construction joints or porous concrete.

Leaks can be sealed easily with a chemical grout material of very low viscosity that forms a gel at a short set time. This grout can be injected into the crack or joint to displace the water, fill the joint and set.

The technique of properly replacing the water with the grout is important. Efficient repair work requires that all available information about the design and construction of the structure should be studied. The extent of the leaking area should be determined. This may require pumping, mopping or even chipping away previously applied surface sealants or gunite. The probably path of the water through the structure to the visible leak should be determined. This is necessary to know where the grout should be placed to do the greatest amount of sealing with the least amount of chemical.

The general approach to remedial grouting, after determining the above information, is to drill small holes in the concrete structure with a rotary hammer and bit. The 1/2-inch (12.7 mm) injection holes are drilled at an angle to the source of the leak. Chemical grout should then be injected through these holes, using a packing at the hole entrance, as indicated in Figure 24 through Figure 29.

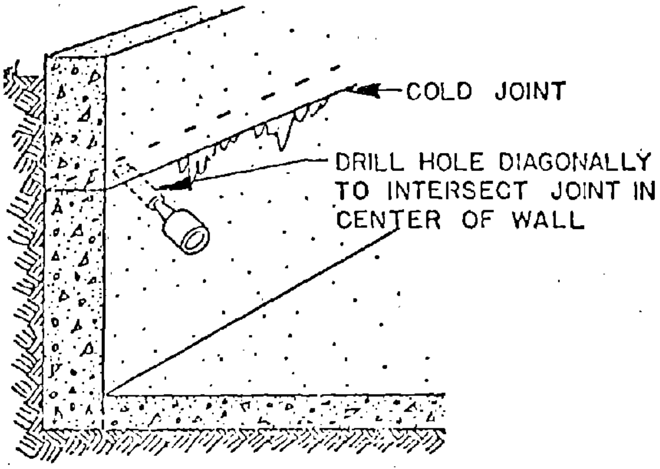


Figure 24. Repair of cold joint

A cold joint is a juncture in a structure formed by placing concrete next to a previous pour that has already set, or at least has taken its initial set. Good bonding is not always achieved and this is a likely place for water entry. Figure 24 indicates the best method to drill and inject the grout. The hole is drilled away from the joint for two reasons: (1) To obtain a good packer seat for the grout point, and (2) To inject grout deep into the concrete wall to form a gasket-like seal through as large a section of the wall as possible.

During injection, the effectiveness of the treatment should be indicated first by water leaking out from the treated zone, and then by the extrusion of dyed grout. It is possible that little indication will be noted on the inside of the structure, but grout may be extruding and setting in the wall and filling the source path. If no indication is noted, pumping should be stopped. If grout is flowing directly out the other side of the wall, it will flow up the wall and do little good. It may then be necessary to drill more holes in and beyond the leaking portion of the joint.

The procedure for sealing a wall or floor crack, as shown in Figure 25, is similar to a cold joint, except that the plane of the crack is not known as it usually is for a cold joint. If the crack is not intercepted by drilling on one side, drill on the other side, being careful not to intersect the original hole with the second hole.

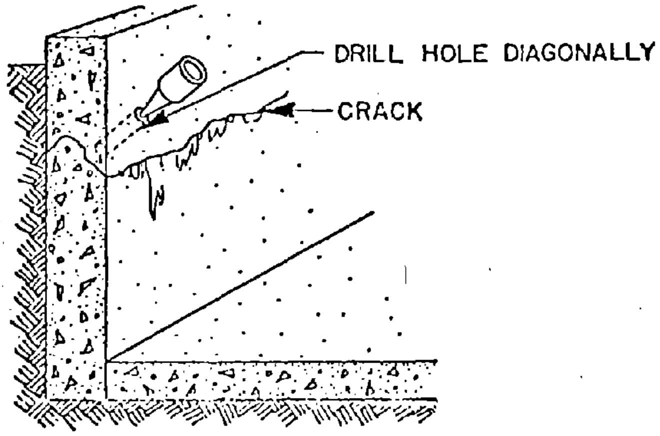


Figure 25. Repair of crack

Figure 26 indicates a pipe penetration and grout point position. Penetration may be conduit, wire, beams or any other object that extends through a concrete wall. The leak is usually on the bottom surface, as this is the area that is hardest to fill when concrete is placed. Usually very small amounts of grout are required.

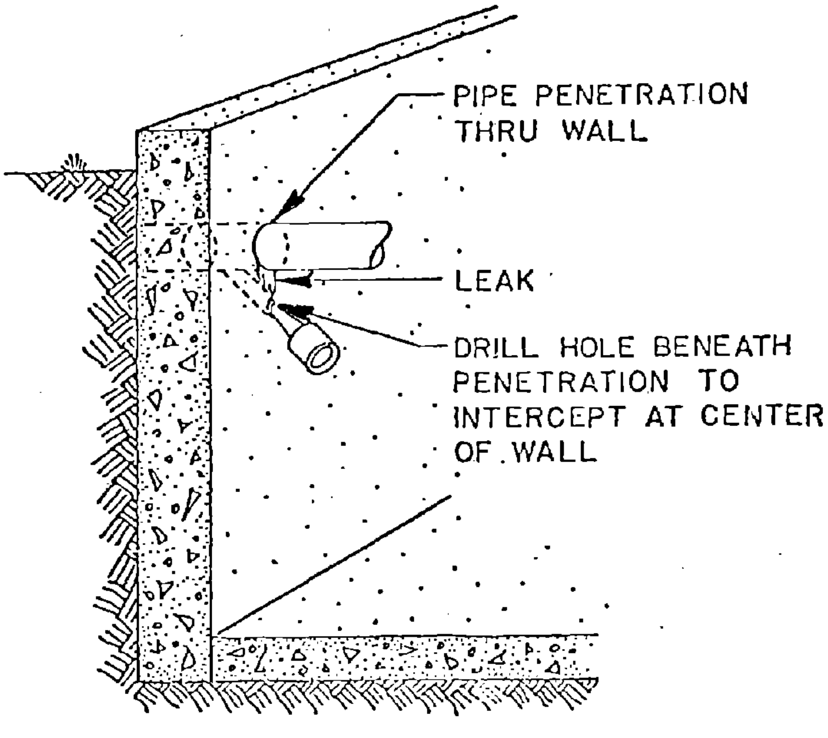


Figure 26. Repair of concrete wall penetration

Figure 27 shows one type of expansion joint. It is better to penetrate the joint material at or below the center of the concrete to keep from having such a direct path out the leak. The flexible material provides a path to extrude grout along one or both faces. Care must be exercised that the grout is pumped slowly enough to (1) prevent pumping out the joint material, or (2) prevent lifting or bulging a thin wall or floor. The grout should have sufficient set time that it will not set quickly and force the joint material out by subsequent pumping.

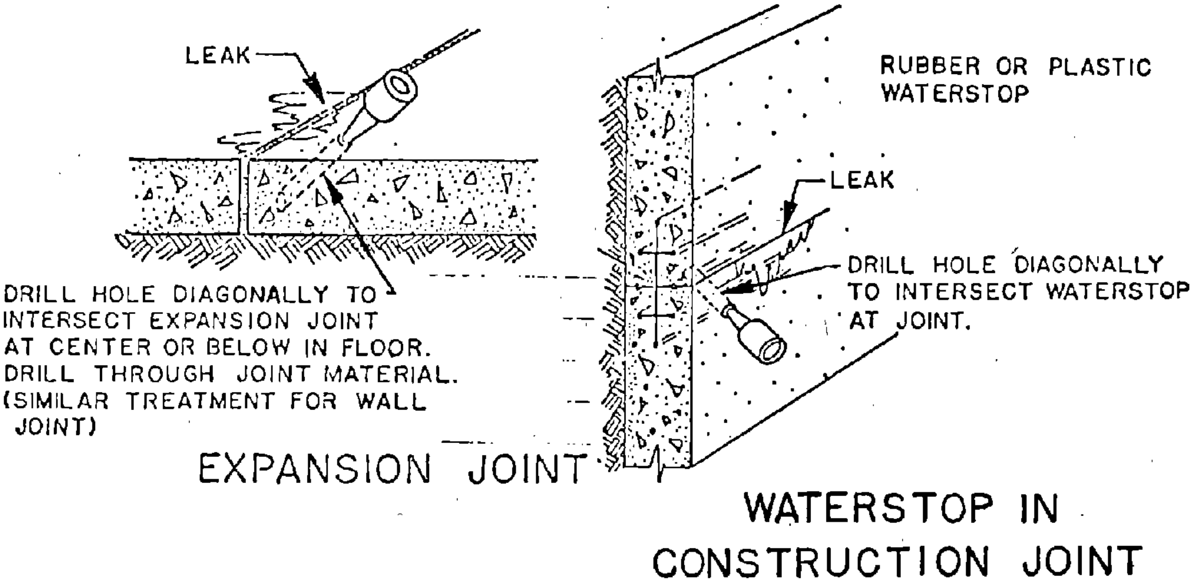


Figure 27. Repair of expansion joint and waterstop in concrete structure

Waterstops placed in construction joints can be treated in a manner similar to expansion joints as the rubber or plastic can flex and allow passage of the grout. The grout hole should be drilled through the stop as close to the construction joint as possible so grout can flow in the joint itself and/or along one or both sides of the stop.

Construction joints may or may not have waterstops. In any event, the grout hole must be drilled through one or more interfaces so that grout can be "squeezed" or pumped into it to form a gasket of grout. In Figure 28 there are several possibilities for drilling. Since water can enter through the wall-floor joint from either side of the footing, it appears that a hole at location "B" would be the best place to drill. Grouting at location "B" will usually solve the problem. In practice, if dimensions are known so that hole "A" can be drilled, experience shows that better distribution of grout can be obtained by injecting at this point. Usually there will be a natural channel along this juncture, and a long section of the leak can be sealed from a single hole. Hole "C" is easiest to drill and the shortest, but may only seal one of the two paths. Hole "D" requires much more drilling and still may only seal one path.

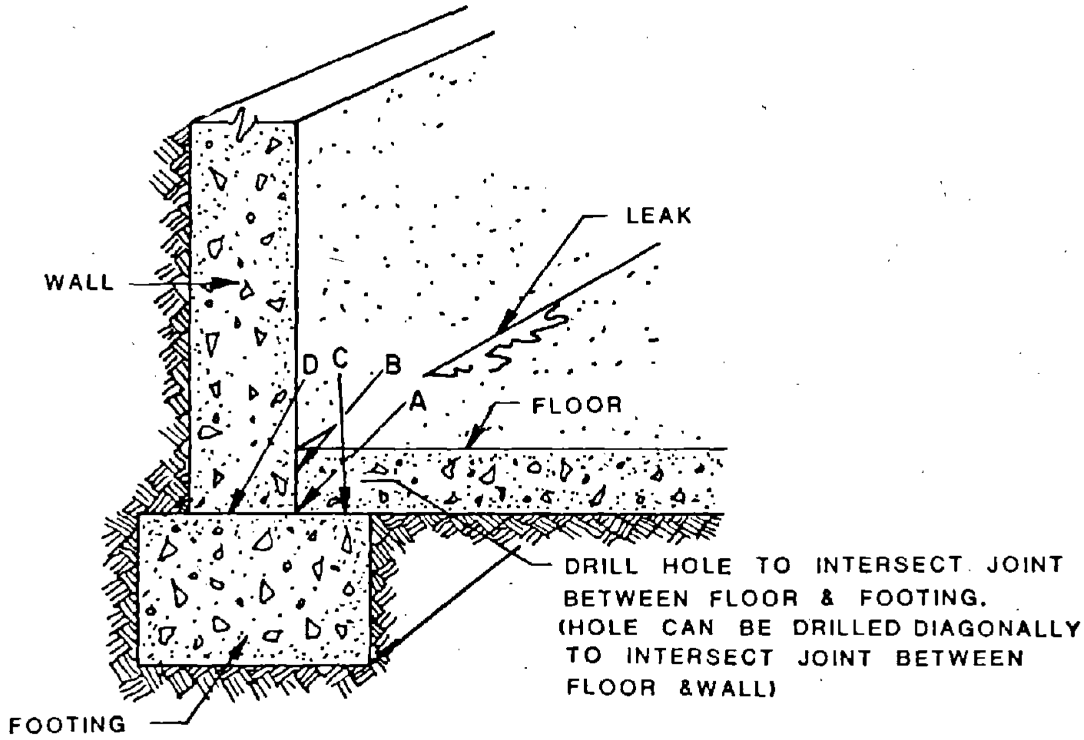


Figure 28. Repair of Construction Joint Leakage

It is difficult to intercept the fluid paths in porous or honeycombed concrete walls. The best possibility is to drill a series of holes below the porous section as shown in Figure 29 and inject small amounts of grout. The grout will usually flow up the wall and tend to flow into the concrete with the water. The grout will also form a mass on the outside that acts as a barrier. By drilling several holes, small amounts of grout can be used in each hole to decrease the possibility of the grout flowing away from the wall in a path of least resistance.

C. GROUTING OF TIEBACK ANCHORS

In developing tieback anchors, the most important factors are the proper installation procedures and the associated hardware. Grouting is but one facet of the installation. The technology of tiebacks is well developed and expertise is evident in the companies listed in the Appendix. The design and construction is also described in detail in publication FHWA-RD-75-130, Volume III, Construction Methods, Lateral Support Systems and Underpinning, Chapter 6, April 1976. Therefore, this subject will be covered only briefly here.

Prestressed rods or cables are generally used as tiebacks. The location of the grouted section is dependent on the soil properties. A theoretical "failure plane" will extend up from the bottom of the

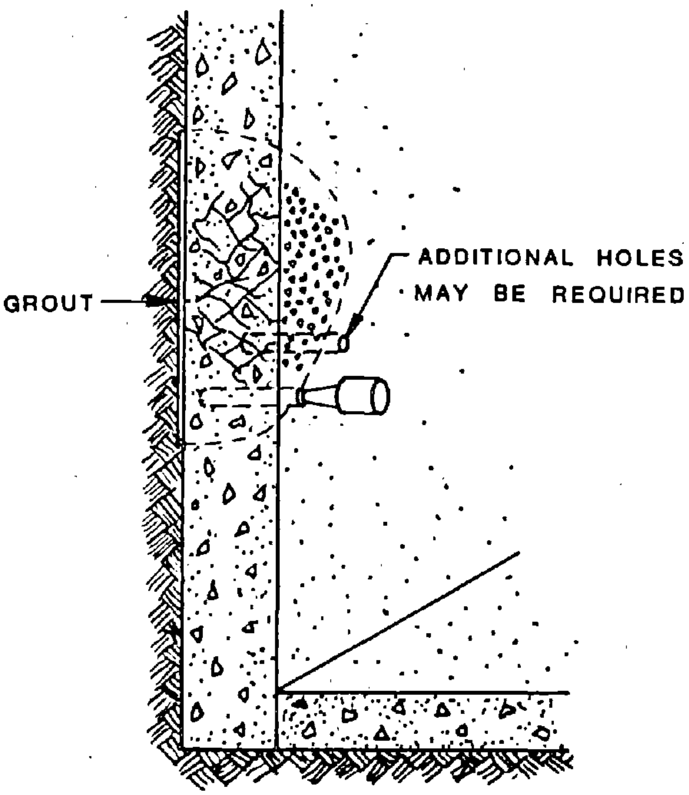


Figure 29. Repair of leakage through porous concrete wall

wall at an angle of 30° to 35° with the vertical. The grouted anchorage must be beyond this "failure plane" to be considered in a safe location. The length of tieback which passes through the theoretically nonbearing soil is greased or wrapped with plastic to prevent bond with the surrounding soil when grouting the anchorage section. Figure 30 gives a typical detail of an earth anchor tieback which uses a steel rod for the stress member. Holes are normally drilled at an angle about 20° to 30° below horizontal. Bore size varies according to the soil and may be from 3 inches to 12 inches in diameter. The length of the grouted section is calculated for the desired load;in some cases the section to be grouted is enlarged by underreaming, or post-grouting is done, in order to provide greater holding strength. Design load per tieback can vary from 50 kips to 100 kips in the United States. Tiebacks are normally post-tensioned to a load of 100% to 150% of the design load, then backed off to the design or working load.

The normal grout material for the anchor is portland cement. Sand is sometimes added to the cement. It has been found that this grout is preferable to an exotic grout because (1) the grout is less expensive (2) additional holding power can be obtained with the cement grout simply by drilling a longer hole and (3) the cement grout is readily available.

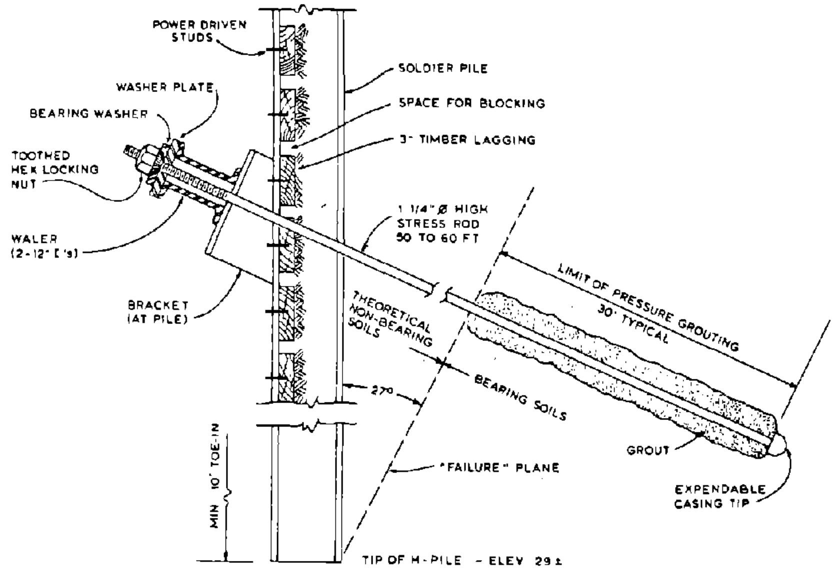


Figure 30. Typical detail of earth tieback anchor

The grout should generally be placed in the hole at low pressures (up to about 50 psi). High pressures are available to prevent fracturing of the soil or formation of discrete lobes. The grout will penetrate into coarse sands and gravel to form an effective anchor. In finer sands or cohesive soils, the grout forms a compacted zone around the anchor which theoretically "locks-in" normal stresses acting on the anchor.

10. APPENDIX

A. Laboratory Test Procedures

Exhibit 1-A, Cohesionless Soil Tests Before and After Grouting

B. Field Test Procedures

Exhibit 1-B - In Situ Permeability-Constant Head - Drive Rod

Exhibit 2-B - In Situ Permeability-Constant Head - Casing & Packer

Exhibit 3-B - In Situ Permeability - Falling Head - Piezometer

C. Grout Materials Suppliers

1. List of Material Suppliers

D. List of Specialists - Tieback Anchors

E. List of Specialists - Slurry Trench and Diaphragm Walls

F. List of Grout Equipment Suppliers

G. List of Grouting Specialists

H. Bibliography (Volume I - Chapter 15)

I. Glossary of Terms

J. References

A. LABORATORY TEST PROCEDURE

EXHIBIT 1-A

COHESIONLESS SOIL TESTS BEFORE AND AFTER GROUTING

A procedure is outlined to determine the engineering characteristics of a soil before and after a grouting operation. A sample of soil is injected with water and with a grouting fluid under controlled conditions. Results include permeability, compatibility of the soil with grouting fluids, and the unconfined compressive strength.

Sample Preparation

The sample should be tested in a state as similar to its original condition as possible. The natural soil moisture and structure should be retained.

Soil Grouting Tests

1. Apparatus and Materials

    a. Thick-wall Pyrex Glass Tubing, 3-4 cm diameter
    b. Threaded Tie Rods, with wing nuts and slotted end plates
    c. One-Hole Rubber Stoppers to fit the glass tubing
    d. Standard-wall Pyrex Glass Tubing, 6 or 7 mm O.D.
    e. Saran Plastic Tubing
    f. Tubing Clamps
    g. Screen, Stainless Steel Wire, 100 mesh
    h. Glass Wool
    i. Compressed Gas Supply (air or nitrogen)
    j. Gas Pressure Regulator
    k. Gas Pressure Gauge, 0 to 50 psig range, or Mercury Manometer
    l. Graduated Cylinders, 100 ml
    m. Stop Watch
    n. Ring Stand, with clamps

2. Procedure (see Figure 31)

    a. Equip rubber stopper with short length of 6-7 mm O.D. glass tubing, with short length of Saran tubing and tubing clamp.

    b. Place a square of screen over the small end of a rubber stopper, positioned to cover the hole in the stopper. Hold it in place with a thin layer of glass wool, pulled taut over the screen and down the sides of the stopper. Insert the stopper firmly into the bottom end of the larger glass tubing, seating by a quarter turn. With a sharp blade, trim excess glass wool from the stopper at the edge of the glass tubing.

c. Pack a representative portion of the soil sample into the large tube to a minimum depth equal to six times the tube diameter.

d. Mount the packed glass tube on a ring stand. Close the tubing clamp on the plastic tubing.

e. Fill glass tube above sample with water.

f. Insert top rubber stopper. Attach end plates to the tube assembly with the threaded tie rods. Tighten end plates against the top and bottom rubber stoppers with the wing nuts on the threaded tie rods.

g. Connect the top end of the sample tube to the compressed air supply through the pressure regulator. Close top tubing clamp. Adjust air pressure to the desired value.

h. Place a graduated cylinder under the bottom sample tube outlet. Open bottom tubing clamp.

i. Open top tubing clamp. Start stop watch.

j. Obtain flow rate through soil sample by flowing water through the soil sample until a stable flow rate is obtained. If necessary, interrupt test to add more water to the sample tube.

k. Bring the water level in the sample within 1/4-inch of the top of the soil column. Close bottom outlet tubing and relieve pressure on the sample tube.

l. The flow rate determined in (j) above is used as a guide to estimate the time required to flow two pore volumes of the selected grouting fluid through the sample and for a check of permeability. The grouting fluid is prepared with the formula that will provide a sufficient fluid time. Prepare an excess of grouting fluid.

m. Inject a minimum of two pore volumes of grouting fluid through the soil sample, using the same temperature and pressure employed in (j) above. Record the fluid time for the unused grouting fluid, and also for the grouting fluid that has passed through the sample.

n. With tube clamps, shut off inlet and outlet tubing on the sample tube. Allow the sample to stand undisturbed during the cure period, which is determined by the type of grouting fluid and the formula used.

o. At the end of the cure period, remove any excess set grouting fluid from the top surface of the soil column. Place water in the tube, and apply the same pressure the soil will experience in actual practice. Determine the flow rate of water through the sample, if any.

p. Using a diamond saw, cut sections of the sample tube containing the grouted sample in lengths not less than 1 1/2 or more than 2 times the diameter of the sand column. Remove the grouted soil cylinders from the glass tube, taking care not to damage them. Store the samples under water until they are tested for unconfined compressive strength.

q. Determine the unconfined compressive strength by placing the sample in the compressive strength tester and applying the load at a rate of 0.14 inch per minute. Record the load value at the moment of failure.

3. <u>Calculations</u>

a. <u>Permeability</u>

The permeability should be calculated for the water flow through the sample both <u>before</u> and <u>after</u> grouting using the following formula:

$$k = \frac{.966uQL}{A(P_1 - P_2)} \times 10^{-3}$$

where k = permeability, cm/sec
Q = flow rate, cc/second
L = soil column length, centimeters
A = soil column cross sectional area, square centimeters
$P_1 - P_2$ = differential pressure, atmospheres
u = viscosity, centipoise

b. <u>Unconfined Compressive Strength</u>

$$\text{Unconfined compressive strength, psi} = \frac{\text{Load, pounds}}{\text{Area, sq. in.}}$$

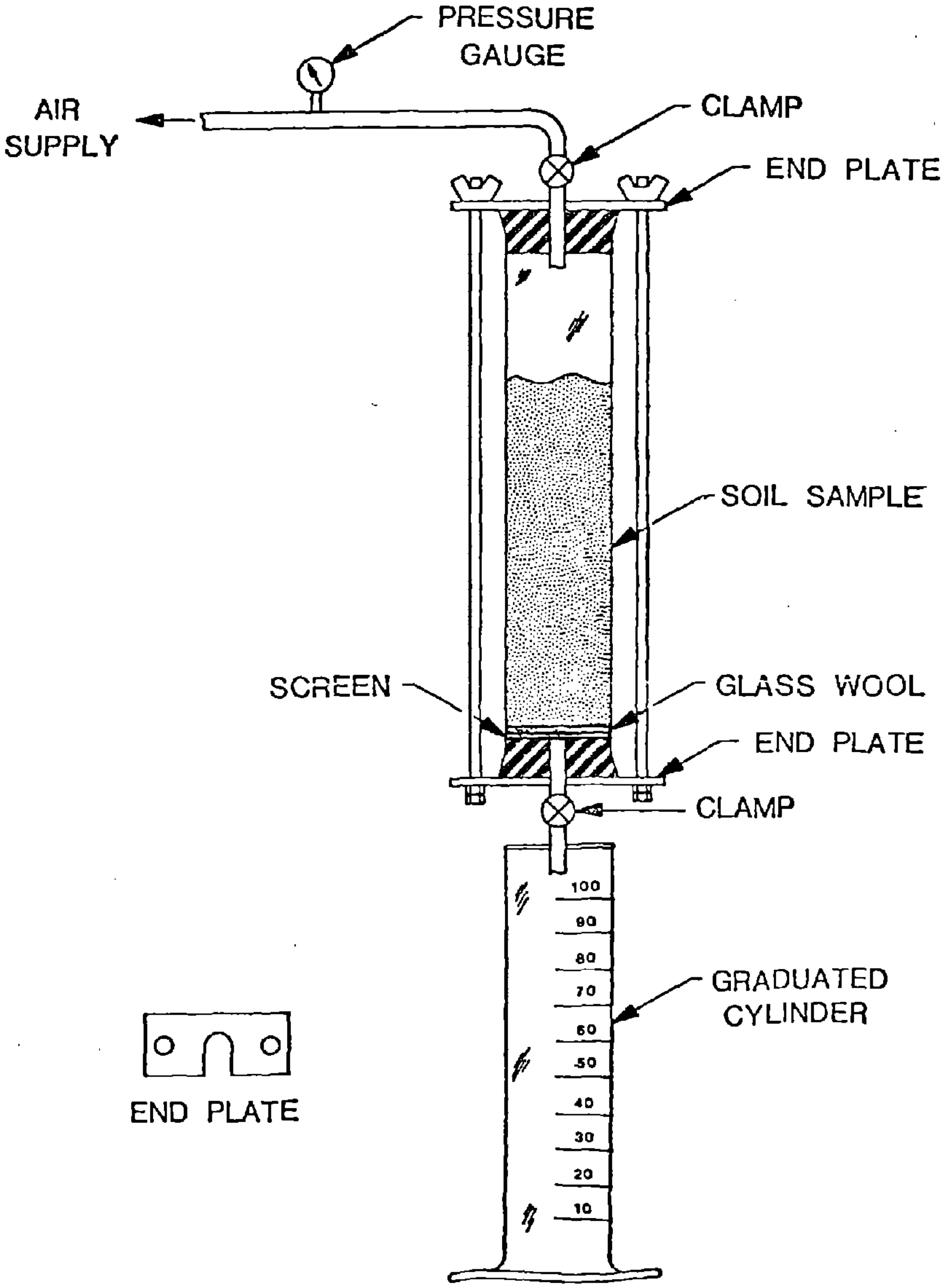


Figure A-1. Soil grouting test setup

B. FIELD TEST PROCEDURES

EXHIBIT 1-B

IN SITU PERMEABILITY TEST - CONSTANT HEAD DRIVE ROD

The drive rod used in the tests can be EX Casing (E Rod), AX Casing (A Rod), BX Casing (B Rod) or NX Casing (N Rod).

Procedure

1. Drive the grout drive rod to the desired depth. The rod should be equipped with a grout point or some protection to prevent filling pipe with soil.

2. Connect the pump to a source of clear water, and install a flow meter in the line to the grout pipe. A suitable tank gauge properly calibrated can be used. Provide an accurate pressure gauge on the pump discharge, and install a bypass line and bleed-off valve upstream from the flow meter and pressure gauge.

3. Start injecting water into the soil. Establish the injection rate at the normal pressure used for grouting. In any event, the pressure at the bottom of the rod should not exceed 1 psig per foot of depth. Maintain the pressure with bleed-off valve on the bypass line.

4. Continue injection for five minutes after a uniform rate-pressure regime has been established. Record all test data.

5. The approximate injection rate for grouting fluid can be estimated from the rate established with water. With all other factors constant, the injection rate with grouting fluid is inversely proportional to its viscosity.

6. To test injectivity at a lower depth, drive the grout rod deeper and repeat the above procedure. Test intervals should be at least five feet apart.

7. Calculate the permeability using the following formula:

$$k = C_1 \frac{Q}{H} (9.665 \times 10^{-7})$$

where

k = permeability, cm/sec
Q = constant rate of flow, gal/min
C_1 = constant, from chart below
H = depth of water in hole, ft.
(or gravity head, ft. + pressure, psi, x 2.31)

Note: When the water table is above the test section, the head is the difference between the level of water in the grout rod and the ground water level plus the injection pressure changed to feet of head. If the stratum is above the water table, the depth of water in the hole is the head.

Values of C_1

EX Csg. (1.5"ID) E Rod	AX Csg. (1.91"ID) A Rod	BX Csg. (2.38"ID) B Rod	NX Csg. (3" ID) N Rod
204,000	160,000	129,000	102,000

EXHIBIT 2-B

IN SITU PERMEABILITY TEST - CONSTANT HEAD CASING WITH PACKER

Casing used in the test can be EX (1.5" ID), AX (1.91" ID), BX (2.38" ID), or NX (3.0" ID).

Procedure

1. Drill to 2 feet below the top of the shallowest interval to be tested. Air or clear water is preferred for drilling, but mud may have to be used to prevent significant sloughing. If drilling mud must be used, drill to the top of the interval with mud, then replace it with clear water when drilling the last two feet into the interval.

2. Run casing to about two feet off bottom of borehole. Equip tubing with an air operated packer and add a two foot tail pipe below the packer.

3. Run tubing string into the hole until the end of the tail pipe is just off bottom. Circulate the hole with clean water until returns are clear.

4. Connect the pump to a source of clear water and through a flow meter to the grout pipe. Provide a pressure gauge on the pump discharge and a bypass line and bleedoff valve upstream from the flow meter and pressure gauge.

5. Inflate the packer in the bottom portion of the casing. Inject clean water into the soil through the tubing.

6. If water returns to the surface through the annulus between the casing and the hole, it will be necessary to seal the casing in the hole before further testing is possible.

   a. Prepare at least ten gallons of acrylamide grout. With the tubing packer set in the bottom of the casing, pump the grout into the hole.

   b. Displace the grout with a volume of water equal to the tubing capacity.

   c. After the grout has set, unseat the packer, pull the tubing and drill the hole two feet deeper, using clear water.

d. With a four foot tail pipe below the packer, run the tubing string. Circulate the hole with clean water until returns are clear.

e. Set the packer just above the bottom of the casing.

7. Start injecting water into the soil. Establish the injection rate at the normal pressure used for grouting. In any event, the pressure at the bottom of the pipe should not exceed 1 psig per foot of depth. Maintain the pressure with the bleedoff valve on the bypass line.

8. Continue injection for five minutes after a uniform rate-pressure regime has been established. Record all test data.

9. The approximate injection rate for grouting fluid can be estimated from the rate established with water. With all other factors constant, the injection rate with grouting fluid is inversely proportional to its viscosity.

10. Additional stratum can be tested by drilling to the desired depth and repeating the steps above.

11. If it is necessary to isolate a deeper test interval from those already tested, a smaller string of casing should be run, and the annulus sealed as in Step 6.

12. Calculate the permeability using the formula below:

$$k = C_p \frac{Q}{H} (9.665 \times 10^{-7})$$

where

k = Permeability, cm/sec
Q = constant rate of flow, gal/min
H = head of water acting on the test length, ft (gravity head, ft + pressure, psi x 2.31)
C_p = constant, from chart below

Note: Where the test length is below the water table, H is the distance in feet from the water table to the swivel plus applied pressure. Where the test length is above the water table, H is the distance in feet from the center of the length tested to the swivel plus the applied pressure.

TABLE B-1

VALUES OF C_p

Length of test section in feet, L	EX (1.5"ID)	AX (1.91"ID)	BX (2.38"ID)	NX (3" ID)
1	31,000	28,500	25,800	23,300
2	19,400	18,100	16,800	15,500
3	14,400	13,600	12,700	11,800
4	11,600	11,000	10,300	9,700
5	9,800	9,300	8,800	8,200
6	8,500	8,100	7,600	7,200
7	7,500	7,200	6,800	6,400
8	6,800	6,500	6,100	5,800
9	6,200	5,900	5,600	5,300
10	5,700	5,400	5,200	4,900
15	4,100	3,900	3,700	3,600
20	3,200	3,100	3,000	2,800

EXHIBIT 3-B

IN SITU PERMEABILITY TEST - FALLING HEAD PIEZOMETER METHOD

Accurate results with this method are possible only when the permeability of soil below the water table is to be determined. Above the water table, air is trapped in the pores of the soil and prevents the necessary accuracy from being obtained.

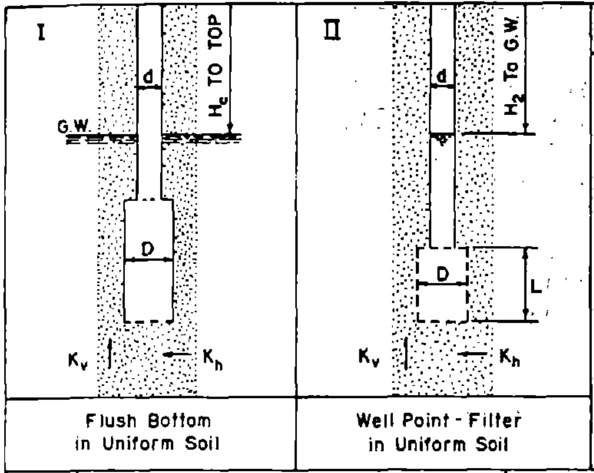
The piezometer is installed in the borehole so that vertical movement of water in the annulus between the borehole and the piezometer tube cannot occur. This is usually done by boring a hole with an auger that will fit snugly inside the piezometer tube, alternately extending the hole with the auger and driving the tube. When the desired depth is reached, a cavity below the end of the tube is drilled to a carefully measured depth. A flexible tube is lowered to the bottom, and the accumulating water is pumped out two or three times, to remove the effect of puddled soil on the cavity walls.

The water level in the tubing is then brought to the ground surface by the addition of water, and maintained until entrapped air has been allowed to escape. The water level is then allowed to drop for a period of 10 to 15 minutes, the rate of drop being recorded at frequent time intervals.

From the known geometry of the hole and the data obtained during the test, a value for the mean coefficient of permeability can be computed, provided that normal groundwater conditions are known.

Figure B-1 illustrates the dimensions and equations employed in arriving at a value for the permeability.

Because of practical difficulties in measurement and time considerations, the falling head permeability test method is usually limited to soils with permeabilities ranging from 10^{-1} to 10^{-4} cm/sec. The principal advantage of the piezometer tube method is the small volume of water required to determine the permeability, and the short time required for significant changes in water level.



Flush Bottom in Uniform Soil

Well Point - Filter in Uniform Soil

LEGEND

D = Diam., Intake, Sample, Cm.
d = Diameter, Standpipe, Cm.
L = Length, Intake, Sample, Cm.
H_c = Constant Piez. Head, Cm.
H_1 = Piez. Head For $t = t_1$, Cm.
H_2 = Piez. Head For $t = t_2$, Cm.
q = Flow of Water, Cm^3/Sec.
t = Time, Seconds
K_v = Vert. Perm. Ground, Cm./Sec.
K_h = Horz. Perm. Ground, Cm./Sec.
K_m = Mean Coeff. Perm., Cm./Sec.
m = Transformation Ratio

$K_m = \sqrt{K_h \cdot K_v}$ $\quad m = \sqrt{K_h / K_v}$

Case	Constant Head	Variable Head
I	$K_m = \frac{q}{2.75 \cdot D \cdot H_c}$	$K_m = \frac{\pi \cdot d^2}{11 \cdot D \cdot (t_2 - t_1)} \ln \frac{H_1}{H_2}$ $K_m = \frac{\pi \cdot D}{11 \cdot (t_2 - t_1)} \ln \frac{H_1}{H_2}$ For d = D
II	$K_h = \frac{q \cdot \ln\left[\frac{mL}{D} + \sqrt{1 + \left(\frac{mL}{D}\right)^2}\right]}{2 \cdot \pi \cdot L \cdot H_c}$	$K_h = \frac{d^2 \ln\left[\frac{mL}{D} + \sqrt{1 + \left(\frac{mL}{D}\right)^2}\right]}{8 \cdot L \cdot (t_2 - t_1)} \ln \frac{H_1}{H_2}$ $K_h = \frac{d^2 \ln\left(\frac{2mL}{D}\right)}{8 \cdot L \cdot (t_2 - t_1)} \ln \frac{H_1}{H_2}$ For $\frac{mL}{D} > 4$

Courtesy: Corps of Engineers
Bulletin #36 - Waterways
Experiment Station

Figure B-1. Formulas for determining permeabilities in boreholes.

C. GROUT MATERIALS SUPPLIERS AND DATA

1. Chemical Grouting Material Suppliers

American Cyanamid Company
Industrial Chemicals & Plastics Division
Wayne, New Jersey 07470
Attn: William J. Clarke

Borden Chemical Company
Division of Borden Company
180 East Broad Street
Columbus, Ohio 43215
Attn: Charles E. Markhott

Diamond Shamrock Chemical Company
Division Technical Center
Paintesville, Ohio 44077
Attn: W. T. Gooding, Manager

E. I. DuPont de Nemours
Wilmington, Delaware

Philadelphia Quartz Company
Public Ledger Building
Independence Square
Philadelphia, Pennsylvania 19106

3M Company
Building 219-1
3M Center
St. Paul, Minnesota 55101
Attn: John F. Evert

D. SPECIALISTS IN USE OF TIEBACK ANCHORS

Bachy, Paris France

The Cementation Co., Ltd.
Cementation House
Mitcham Road
Croydon, Surrey, England

Consonda, Milan, Italy

Geosonda
Via Girolamo da Capri, 1
Roma, Italy

ICOS
Via Luciano Manara, 1
20122 Milano, Italy

Nederhorst Grondtechniek
Postbus 177
Gouda, Holland

Ing G. Rodio C.S.P.A.
Strada Pandina
2007 Casamalocco (MI) Italy

Soletanche Entreprise
7, rue de Logelback
75017 Paris, France

Spencer, White and Prentiss
10 East 40th
New York, New York

Warren-Fondedile, Inc.
675 Massachusetts Avenue
Cambridge, Massachusetts 02139

E. SPECIALISTS FOR SLURRY TRENCH & DIAPHRAGM WALLS

Antwerpse Bouwwerken Verbeeck
Bouwensstraat 29-35
Antwerpen, Belgium

Bachy
Paris, France

The Cementation Co., Ltd.
Cementation House
Mitcham Road
Croydon, Surrey, England

Consonda
Milan, Italy

Geosonda
Via Girolamo da Capri, 1
Roma, Italy

ICOS
Via Luciano Manara, 1
20122 Milano, Italy

Nederhorst Grondtechniek
Postbus 177
Gouda, Holland

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Strada Pandina
2007 Casamalocco (MI)Italy

Soletanche Entreprise
7, rue de Logelback
75017 Paris, France

Spencer, White and Prentiss
10 East 40th
New York, New York

Warren-Fondedile, Inc.
675 Massachusetts Avenue
Cambridge, Massachusetts
02139

F. GROUTING EQUIPMENT SUPPLIERS

Company	Type of Equipment
Chem Grout La Grange Park, Illinois	Cement Slurry Equipment Chemical Grout Equipment
Gardner Denver Quincy, Illinois	High-Pressure Portland Cement Pumps
Halliburton Services Duncan, Oklahoma	Low Volume, High Pressure Chemical Pumps Two-Stream Grout Manifold Grout Drive Rods Grout Packers
Kerr Pump Company Ada, Oklahoma	High Pressure Chemical Pumps
Robins and Meyers Springfield, Ohio	Portland Cement and Chemical Low-Pressure Pumps

G. LIST OF GROUTING SPECIALISTS

Grouting Specialists in the United States

Alabama Waterproofing Company, Inc.
P. O. Box 692 - Route 18
Birmingham, Alabama 35210
Attn: Will Max Harden

Hayward Baker Company
1875 Mayfield Road
Odenton, Maryland 21113
Attn: Wallace H. Baker, President

Chemgrout Incorporated
805 East 31st Street
LaGrange Park, Illinois 60525
Attn: Doring Dahl, President

Chemical Soil Solidification Company, Inc.
1728 Broadway
Hewlett, Long Island 11557
Attn: Martin Riedel, President

Chemical Soil Solidification Company, Inc.
7650 South Laflin Street
Chicago, Illinois

Dean Jones Contractor
410 Opal Street
Clinton, Oklahoma 73601
Attn: Dean Jones, President

Eastern Gunite Company
240 Rock Hill Road
Bala Cynwyd, Pennsylvania 19004
Attn: P. A. Heaver, President

Foundation Sciences, Inc.
Cascade Building
Portland, Oregon 97200
Attn: Ken Dodds, President

Geologic Associates, Inc.
Reynolds Road
Franklin, Tennessee 37064
Attn: Raymond T. Throckmorton, Jr., President

Geron Restoration Company
7 Wells Street
Saratoga, New York 12866
Attn: Gerald Benoit, President

Halliburton Services
P. O. Drawer 1431
Duncan, Oklahoma 73533
Attn: Tom Lenahan, Grouting Consultant

Halliburton Services
Nine Parkway Center - Suite 275
Pittsburgh, Pennsylvania 15220
Attn: Lloyd Wantland, Superintendent

Hunt Process Company, Inc.
P. O. Box 2111
Santa Fe Springs, California 90670
Attn: Slade Rathbun, Manager

Intrusion Prepakt Company
13224 Shaker Square
Cleveland, Ohio 44120
Attn: Bruce Lamberton, Vice President

Northern Systems, Inc.
20702 Aurora Road
Cleveland, Ohio 44146
Attn: Ray Tartabini, President

Penetryn Systems, Inc.
424 Old Niskayuna Road
Latham, New York 12110
Attn: Ed Stringham, President

Pressure Grout Company
1680 Bryant Street
Daly City, California 94015
    Attn: Ed Graf, President

Raymond International, Inc.
Soiltech Department
6825 Westfield Avenue
Pennsauken, New Jersey 08110
    Attn: Joe Welsh, Manager

SOLINC
Soletanche and Rodio, Inc.
6849 Old Dominion Drive
McLean, Virginia 22101
    Attn: Gilbert Tallard, General Manager

Terra-Chem, Inc.
P. O. Box 46
George's Road
Dayton, New Jersey 08810
    Attn: Herbert L. Parsons, President

Warner Engineering Services
2905 Allesandro Street
Los Angeles, California 90039
    Attn: James Warner, President

Core Drilling - Grouting Specialists

Boyles Brothers Drilling Company
P. O. Box 58
Salt Lake City, Utah 84110
Attn: F. E. Sainsbury, Vice President

Continental Drilling Company
2810 North Figueroa Street
Los Angeles, California 90065
Attn: Richard O. Theis, President

Robert P. Jones Drilling Company
3512 North 36th Street
Boise, Idaho 83703
Attn: Robert P. Jones, President

W. J. Mott Contractor Inc.
817 - 8th Avenue
Huntington, West Virginia 25701
Attn: William H. Mott
F. C. Stump

Pennsylvania Drilling Company
1205 Chartiers Avenue
Pittsburgh, Pennsylvania 15220
Attn: Thomas B. Sturges, Vice President

Freezing

Terrafreeze Corporation
8551 Backlick Road
Lorton, Virginia 22079
Attn: John Shuster, Manager

Grouting Specialists in Europe

Soil Mechanics, Ltd.
Foundation House
Eastern Road
Bracknell, Berkshire, England

Soletanche Entreprise
7, rue de Logelback
75017 Paris, France

Bachy
Paris, France

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Consonda
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ICOS
via Luciano Manara, 1
20122 Milano, Italy

Keller Division
Guest, Keen &
Nettlefords, Ltd.
Frankfurt, Germany

I. GLOSSARY OF TERMS

Activator - Catalyst or hardner, reactant - the chemical solution which causes a mixture to gel or set when mixed with the base solution.

Alluvium - Clay silt, sand, gravel or other rock materials transported by flowing water and deposited in comparatively recent geologic time as sorted or semisorted sediments, in riverbeds, estuaries and flood plains, on lake shores and in fans at the base of mountain slopes.

Backpack Grouting - The filling with grout of the annular space between the permanent tunnel lining support and the sediments.

Bentonite - A montmorillonite type clay formed by the alternation of volcanic ash which swells in the presence of water.

Catalyst - See Activator

Changed Conditions or Differing Site Conditions - Subsurface or latent physical conditions at the site differing materially from those indicated in a contract; or nature, differing materially from those ordinarily encountered and generally recognized as inherent in work of the character provided for in the contract, which conditions can bring about an equitable adjustment to modify the contract.

Compaction Grouting - Intruding a mass of viscous cement grout into cohesionless soil to fill voids and to compact the soil by pressure. If performed in cohesive soil this is known as Compensation or Displacement grouting.

Consolidate, Consolidation Grouting or Solidify - Terms applied to the binding together of soil particles into a mass of soil, such as occurs in permeation grouting (see permeation grouting).

Cut-and-Cover Tunneling- A process of installing a structure below ground by excavating an area of sufficient width, constructing the permanent structure at the bottom of the excavation, and then covering the structure with soil.

Deformability - A measure of the elasticity of the grout to distort in the interstitial spaces as the sediments move.

Diaphragm Walls - The construction of a vertical, continuous concrete wall, cast in situ or made of precast concrete panels, in a narrow trench to form a structural retaining wall for unconsolidated sediments.

Fracturing, Fracturing Treatment or Fracture Grouting - Grouting performed using an injection pressure usually considerably higher than the overburden pressure, which opens cracks or channels in the soil deposit. The grout then fills these channels and frequently forms lenses.

Gel Time - See Setting Time

Groundwater Table - The level below which the rock and subsoil are full of water.

Grout - A suspended cement slurry or chemical solution that can be poured or forced into the openings between soil or rock particles to solidify or to change the physical characteristics of the material.

Groutability - The ability of soil to allow grout to be forced into the interstitial spaces between the particles.

Groutability Ratio - The ratio of the 15 percent size of the formation particles to be grouted to the 85 percent size of the grout particles (suspension-type grout). This ratio should be greater than 24 if the grout is to successfully penetrate the formation.

Grout "Take" - The measured quantity of grout injected into a unit volume of formation or soils.

Hydrostatic Head - The pressure in the pore water produced by the height of water surface above a given point.

Injectability - See Groutability

In Situ - Applied to a rock, soil or fossil when occurring in the situation in which it was originally formed or deposited.

Joosten Grouting - The earliest of the chemical grout processes, originating in 1925. By this process, a sodium silicate solution is pumped into the soil as a grout pipe is advanced downward. The pipe is then flushed with water, and calcium chloride is pumped in as the pipe is retracted. A precipitate forms upon contact between the two solutions.

Mixed Face - The face of a tunnel which consists of unconsolidated soil and hard rock.

Mud Jacking - A process in which a hole is bored through a concrete slab which has subsided and a water-soil cement slurry is pumped under the slab to raise and support it.

Newtonian Fluid - A true fluid which tends to exhibit constant viscosity at all rates of shear.

Non-Newtonian Fluid - Not a true fluid and does not exhibit constant viscosity at all rates of shear.

Perched Water Table - A water table usually of limited area maintained above the normal free water elevation by the presence of an intervening relatively impervious confining stratum.

Permeability - The ability of a formation or material to transmit a fluid.

Permeation Grouting - Replacing the water in voids between the grain particles with a grout fluid at a low injection pressure to prevent creation of a fracture, permitting the grout to set at a given time to bind the soil particles into a soil mass.

Porosity - The ratio of the volume of the voids or pores to the total volume of the soil.

Proprietary - Made and marketed by one having the exclusive right to manufacture and sell; privately owned and managed.

Pumpability - A measure of the properties of a fluid or cement slurry grout to be pumped.

Reactant - See Activator

Resin - A synthetic addition or condensation polymerization substance or natural substance of high molecular weight, which under head, pressure, or chemical treatment becomes a solid.

Setting Time - A term defining the hardening time of Portland Cement or the gel time for a chemical grout.

Slurry - Suspension of cement or clays in water or a mixture of both.

Slurry Trench - A relatively narrow trench which is usually dug with a clamshell while the excavated portion is kept filled with a bentonite slurry to stabilize the walls of the trench.

Syneresis - When freshly prepared sodium silicate gel is placed in a closed glass container, a significant amount of water can be observed being extruded by the gel. This is the phenomenon of syneresis.

Toxicant - A poisonous agent.

True Solution - One in which the components are 100% soluble in the base solution.

Tube a' Manchette - A plastic tube (pipe) perforated with rings of small holes at intervals of about 12 inches. Each ring of perforations is enclosed by a short rubber sleeve fitting tightly around the pipe so as to act as a one-way valve when used with an inner pipe containing packing elements which isolate a hole for injection of grout.

Tunnel Face - The principal frontal surface presenting the greatest area such as the face of a pile of material, the point at which material is being mined.

Unconfined Compressive Strength - The load per unit area at which an unconfined prismatic or cylindrical specimen of material will fail in a simple compression test.

Void Ratio - The ratio of the volume of void space to the volume of solid particles in a given soil mass.

Water-Cement Ratio - The ratio by weight of water to the total solids in a cement slurry.

Water Intrusion - The flowing of water into unwanted areas such as trenches and tunnels.

J. REFERENCES

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   c. Engineer Manual EM 1110-2-3503, Foundation Grouting: Field Technique and Inspection, Department of Army, Office of Chief of Engineers.

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